

Review

Offshore wind farm impacts on marine fauna across taxa and ecological levels: A global review

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SUMMARY

The expansion of offshore wind farms (OWFs) is central to global decarbonization strategies, yet their effects on marine biodiversity are only partially understood. This systematic review synthesizes 221 publications up to June 2025 to assess the ecological impacts of OWFs on marine fauna living below the sea surface. The evidence base is uneven, heavily focused on North European waters, fish, and invertebrates, while expanding OWF regions and marine mammals remain underrepresented. Most studies examine short-term, individual-level responses, limiting inference on long-term effects. Impacts vary widely by stressor, taxon, and biological outcome. Invertebrates often show positive responses linked to reef effects, though key functional traits are vulnerable. Fish responses are largely neutral except under noise, while marine mammals exhibit the most consistent negative impacts. The impact score developed here highlights taxon-specific vulnerability and offers a scalable risk-assessment tool for data-poor regions. The review calls for standardized, long-term field monitoring to support OWF expansion while safeguarding biodiversity.

INTRODUCTION

Over the past decade, global electricity production from renewable energy has grown exponentially, driven by technological advances, declining production costs, and strong support from governments and investors.¹ In particular, offshore renewables (ORs) are gaining global momentum, as they are considered a key component of the future energy mix needed for decarbonization and climate neutrality.² Further, ORs enhance local energy production while reducing reliance on fossil fuel transport and associated spill risks, positioning it as a strategic renewable source for energy security and resilience.^{3,4} This is reflected in increasingly ambitious national targets, such as the EU's collective aim to reach 111 GW of offshore capacity by 2030—nearly double the level set in its 2020 Offshore Renewable Energy Strategy—and similar commitments emerging worldwide.

In 2024, global offshore wind capacity reached 83.2 GW, making it the fourth-highest year for new installations.⁵ China was the leading country for the seventh consecutive year, installing 4 GW and bringing its total offshore wind capacity to 41.8 GW. Europe added 2.7 GW in 2024, accounting for about one-third of global additions, mainly due to installations in the United Kingdom, Germany, the Netherlands, and France.⁵ In Asia, new offshore wind capacity was also commissioned in Taiwan, Japan, and South Korea, while in the Americas, only the United States currently has operational offshore wind turbines.⁵

In 2024, global installed floating wind capacity reached 278 MW. This refers to wind turbines mounted on floating substructures anchored by mooring or station-keeping systems,

rather than fixed to the seabed, allowing deployment in deeper waters where fixed-bottom foundations are impractical. The largest installations were in Norway (101 MW), the United Kingdom (78 MW), and China (40 MW), with additional capacity in France, Portugal, Japan, and Spain. The Global Wind Energy Council estimated that more than 350 GW of new offshore wind capacity will be added between 2025 and 2034, increasing global capacity to 441 GW by the end of 2034. OR energy is therefore expected to play a crucial role in supporting countries worldwide to meet their energy transition and climate goals and reducing dependence on imported fossil fuels.

Although the decarbonization benefits of OR energy are well established, the environmental impacts of these structures on marine biodiversity deserve particular attention—especially given their expected widespread expansion. A growing body of scientific research has documented the various ecological effects associated with offshore wind farms (OWFs).^{3,6–9} These impacts occur throughout the life cycle of OWFs—from construction to operation and eventual decommissioning—and can vary significantly depending on regional oceanographic conditions, depth, turbine technology (e.g., fixed vs. floating), and the sensitivity of local ecosystems.³

During construction, pile driving and seabed disturbance are known to generate high-intensity underwater noise, increase sediment plumes, and temporarily displace or stress sensitive marine fauna, particularly marine mammals and fish.^{10–13} In the operational phase, ongoing low-frequency noise and electromagnetic fields (EMFs) from underwater cables may alter the behavior, migration, and feeding patterns of both demersal and



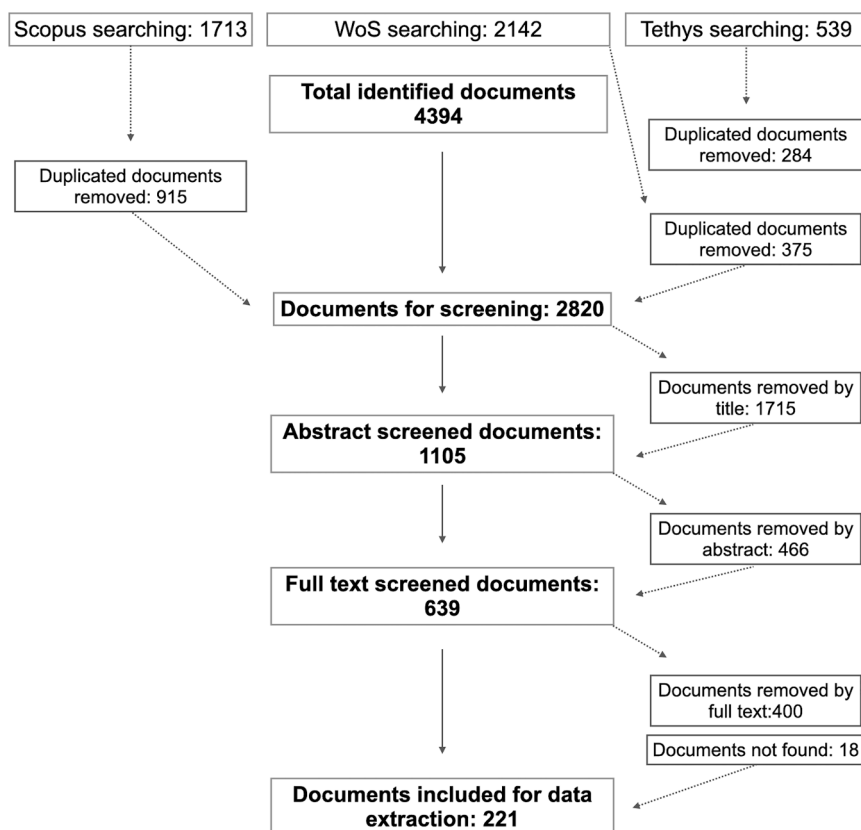


Figure 1. Flow diagram (based on the PRISMA protocol) showing the selection process of the systematic literature review

score (IS) aimed at providing a quantitative estimate of each species' potential exposure to OWF impacts, offering insights into the transferability of ecological responses across marine regions.

RESULTS AND DISCUSSION

To map global research, the systematic literature search was performed in Scopus, Web of Science and Tethys (<https://tethys.pnnl.gov>) using a search string combining keywords related to offshore wind energy with several marine fauna taxa referring terms. Studies were included if they provided primary empirical data (field or laboratory) assessing faunal responses to OWF stressors, while reviews and gray literature were excluded (see [methodology](#) section for full details).

The electronic search initially identified 4,394 documents, which were reduced to 2,820 after duplicate removal. The screening process then excluded 2,599 documents based on title, abstract, and

full-text screening. A total of 221 documents ([Data S1](#)), comprising 1,119 case studies, finally met the inclusion criteria ([Figure 1](#)).

Existing knowledge and research gaps Temporal and spatial patterns

The number of studies addressing the ecological impacts of OWFs on marine fauna has increased markedly over the past two decades ([Figure 2](#)). Between 2005 and 2010, only <10% of the total studies were published each year. Publication output accelerated after 2015 and peaked between 2021 and 2025, reflecting a growing global research focus on ORs and marine biodiversity coinciding with the expansion of OWF installations in Europe and Asia.⁵ Further, the thematic focus of the literature has diversified over the past two decades. Between 2006 and 2013, research was strictly limited to the direct impacts of the physical presence of turbines and related infrastructure and underwater noise/marine traffic. Conversely, the subsequent decade marked a clear evolution in research priorities: electromagnetic pollution assessments emerged strongly from 2014 onward, while investigations into chemical pollution appear almost exclusively within the last few years (2020–2025).

Consistent with other recent reviews,^{7,9,20} most study sites were in the North Sea and adjacent European waters (particularly in the United Kingdom, Germany, Denmark, and the Netherlands), which together accounted for most of the total research ([Figure 3](#)). Our result may be explained both by the

pelagic species.^{14–16} However, OWFs can also produce positive ecological effects, such as creating artificial reef habitats that enhance local biodiversity by providing hard substrates for benthic communities, including commercially important shellfish and other invertebrates.^{17,18} Additionally, exclusion zones around turbines often reduce human activities such as fishing and shipping, potentially functioning as *de facto* marine protected areas.¹⁹

Understanding the impact of OWFs on marine biota has become an urgent need as OWF capacity expands globally and project approval also relies on impact assessments. This study offers an updated synthesis of current understanding regarding the impacts of OWF development on marine biodiversity, based on a systematic literature review that extends and complements prior reviews, including recently published ones.^{3,7–9,20} Unlike prior narrative, single-topic,^{6,10,13,21–26} or regional^{19,27–30} reviews, this study offers a comparative analysis to identify consistent patterns and critical knowledge gaps, providing a framework to guide ecologically informed planning of future developments. Importantly, the review considers multiple ecological levels (species, population, and community) of marine fauna, encompassing both benthic and nektonic groups, and highlights the impact on both protected and commercially important species, identifying broad ecological patterns and cross-taxon trends. Furthermore, information on species susceptibility, distributional range, conservation status, and evidence reliability was used to calculate an integrated impact

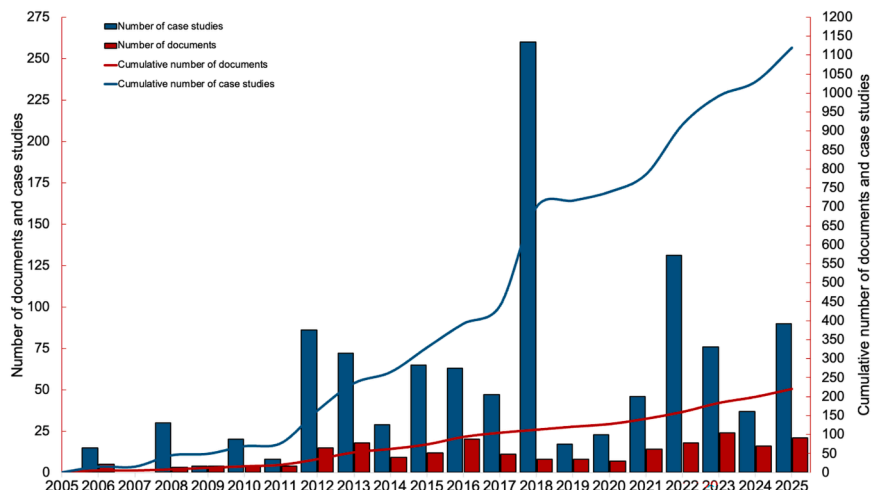


Figure 2. Temporal pattern of published studies from January 2005 to June 2025

based studies allow to measure critical aspects related to individual behavior that can have cascading effects on populations and communities. These include changes in movement patterns, foraging activity, breeding or spawning aggregations, and vocalization behavior that may affect predation risk, predation success rates, reproductive success, and population size and structure.³³

Among exposure types, the physical presence of structures and EMFs were the most frequently investigated

higher number of OWF installations in these European countries and by the language restriction applied during the literature search (English), which excludes publications in other languages (e.g., those from Asian regions). In fact, in recent years, some case studies have emerged from China and Japan, reflecting the expansion of OWFs into non-European regions.⁵

Study duration ranged from short-term field surveys (<1 year) to long-term monitoring exceeding 3 years (14%), although short-term investigations dominated the dataset (42%, Figure 3). This result represents an additional limitation in our ability to understand the impacts of OWFs on marine biodiversity, particularly for long-lived species, as ecological responses may differ substantially depending on the temporal scale considered.^{31,32}

Type of experiment and exposure

To ensure a rigorous and reproducible analysis, our systematic review was structured around the formalized PECO (population, exposure, comparator, outcome) protocol (see Table 1 for full details). This framework explicitly separates the direct environmental stressors (the exposure: physical, chemical, electromagnetic, or acoustic alterations introduced by wind farm infrastructure and activities) from their cascading ecological impacts (the outcome) across three distinct ecological levels (species-level traits, population-level dynamics, and community-level changes). Further, studies were classified based on the phases of the OWFs (construction, operation, and decommissioning) and the type of experimental design (laboratory- or field based).

About 40% of case studies examined impacts occurring during the construction (10%) and operational phases of OWFs (29%), and they investigated impacts mostly related to the physical presence of turbines and related infrastructure and noise/marine traffic (26% and 8% of studies, respectively, Figure 4). Further, experiments were largely laboratory based (57%), while observational *in situ* field studies (41%) were less common, and model assessments were rare (1%). This laboratory bias and the paucity of field studies impede robust and generalizable conclusions,³ limiting ecological inference and transferability to field conditions.³³ Further, only field-

stressors—42% and 34% of studies, respectively—followed by underwater noise (28%) and chemical disturbances (1%) (Figure 4).

In recent decades, concerns regarding the environmental impacts of OWFs have been increasingly expressed, particularly by the fishing community. As a result, most studies to date have focused on commercial species, often examining the “refuge effect” (where marine species use OWFs for feeding and/or shelter) and the “artificial reef effect” (where OWF structures provide novel habitat, promoting colonization by benthic and demersal assemblages) associated with the physical presence of turbines and related infrastructure.³⁴ Another aspect that may have driven research on OWF structures is the risk of entanglement for highly mobile and often highly protected species, such as marine mammals, sharks, and sea turtles.³⁵

EMFs originate primarily from subsea power-transmission cables, including both the cables emerging from individual turbines and those connecting the OWF to the onshore grid. The effects of EMFs have received considerable scientific attention because several elasmobranch species (e.g., sharks and skates) and some fish, including salmonids, are known to be sensitive to electric fields, while certain benthic invertebrates and marine mammals may respond to magnetic fields.^{36–38}

Noise can be generated during both the construction and operational phases of an OWF. It arises from pile driving and other construction activities, turbine rotation, and increased vessel traffic in the surrounding area. The intensity and periodicity of this noise are highly variable and depend largely on turbine mooring type, turbine size and density, and local oceanographic conditions. The widespread sensitivity of marine organisms to anthropogenic noise and the pervasive nature of its ecological effects have been documented for decades.^{31,32} Most studies conducted in coastal habitats, as well as in neritic and oceanic environments, have reported negative responses to noise exposure, primarily at the species and population levels.³² Consequently, noise generated by OWF installations has been extensively investigated so far.

Finally, in the OWF sector, potential chemical emissions may arise from multiple sources, including increased marine traffic

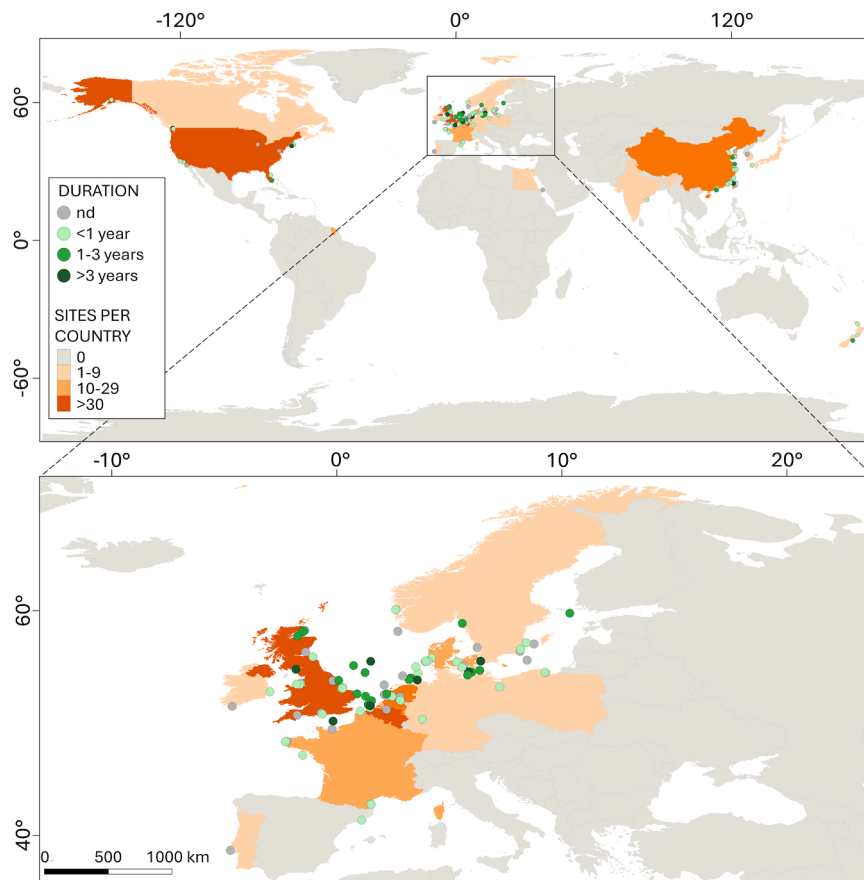


Figure 3. Number of study sites per country and duration of the study, with a focus on the European region where most studies were located

Due to the high density of studies and the dot size required for global visibility, some dots may slightly overlap onto adjacent landmasses, even if the studies strictly focus on marine environments.

graphic dynamics, while community-level studies remain particularly limited, likely due to the inherent challenges of conducting them in the field. Complex processes, such as trophic shifts and cascading effects within food webs, cannot be inferred from single-species response data.⁸ Together, these gaps constrain robust assessments of ecosystem-scale impacts, limiting our ability to evaluate the broader consequences of OWFs and to infer their impacts on ecosystem services.

Impact of OWFs on marine biodiversity

Considering the overall impact of OWFs on marine biodiversity, almost half of the studies (49%) reported no detectable changes, while smaller proportions documented negative (28%) or positive (23%) impacts. This result apparently contrasts

and associated spill risks, disturbance of contaminated sediments during cable installation or foundation works, discharges from wastewater treatment and cooling systems, leaching from synthetic scour-protection materials, and accidental releases during emergency events.³⁹ Since engineering and operational safeguards can reduce the likelihood of such events, chemical pollution has remained an underexplored stressor until recently and still appears underrepresented in the current literature.

Taxa, ecological levels, and outcomes

Research effort was unevenly distributed among taxonomic groups (Figure 5). Fish and invertebrates represented the most frequently studied groups (55% and 33%, respectively), while marine mammals were less studied (12%). This trend appears to be a recent development, as previous reviews identified benthic invertebrate communities as among the least investigated.^{3,38} Regarding the ecological level, most studies focused on species individual traits (61%), examining physiological or behavioral responses (Figures 6 and 7). Population-level analyses were less frequent (19%)—mainly addressing changes in size and spatial traits (Figures 6 and 7)—as well as community-level perspectives (20%), exploring biodiversity patterns (richness, abundance, and diversity). The predominance of species trait-based laboratory studies provides insight into short-term physiological or behavioral responses but offers little information on long-term or cumulative effects. The scarcity of population-level analyses reduces our ability to detect changes in demo-

with the findings of some recent reviews,^{3,6,9} which found the highest percentage of negative impacts. First, this inconsistency may be due to several methodological aspects linked to different periods of investigation, inclusion criteria, and search strategies. Second, such inconsistency highlights the need for a standardized definition of impact on biodiversity and assessment protocols³³ as well as clearer impact-classification schemes. Further, coordinated large-scale monitoring efforts and improved data accessibility would enhance the reliability of future assessments and support more informed management of OWF development.

Impacts differed strongly among taxonomic groups. For invertebrates, most studies (40%) reported positive impacts, whereas most studies on fish (66%) found no measurable changes. In contrast, studies on marine mammals predominantly (71%) documented negative impacts (Figure 8). These impacts, which varied substantially depending on the type of exposure and the assessed outcome, are presented and discussed in detail later.

Invertebrates

One-third of the selected case studies concerned invertebrate species ($n = 365$). Most of the studies were conducted under laboratory conditions, whereas only a small proportion were carried out in the field, primarily during operational phases (Figure 8).

OWFs seemed to have a positive impact on invertebrates (40% of the total case studies). These benefits were mostly related to community abundance, diversity, and richness. Neutral outcomes (34% of the total case studies) were

Table 1. Population, exposure, comparator, and outcome criteria applied in the systematic review

Population (P): the ecological level that constituted the study unit exposed to offshore wind farms	marine animal species, population, community (excluded seabirds and phytoplanktonic organisms)
Exposure (E): action to which the subject populations are exposed	wind farm installations in marine environments and related effects (as introduced pollutant, activity, or structure): ● physical structure (e.g., foundations, anchors, and cables) ● chemical pollution (e.g., displacement of contaminated sediments during seabed works for cables and foundations or dispersal from synthetic scour-protection materials) ● electromagnetism (electric and magnetic fields due to the power transmission stations and cables) ● underwater noise and marine traffic (e.g., noise produced during construction, turbine operational noise, and noise due to marine traffic)
Comparator (C): either a control with no intervention/exposure or an alternative intervention or a counterfactual scenario	absence or gradient of exposure
Outcome (O): any response variable related to population (P) and associated to the exposure (E) that can be reliably measured	response variables related to different ecological levels (species, population, and community) associated with exposure to offshore wind farms and related impact: - species ● performance (e.g., somatic growth, mortality, injuries, and reproduction) ● functional (e.g., feeding, behavior, energy budget, metabolism, and respiration) - population ● population size ● demographic structure ● spatial traits (geographical range, home range, habitat use, and migration) - community ● species richness ● diversity ● abundance

associated with avoidance and population spatial traits, while negative impacts (26% of the total case studies) were mainly associated with injuries or trauma, reproduction, navigation, energy budget/metabolism, and other behavioral responses (Figure 9). This pattern suggests that, although many invertebrate responses to wind-farm exposures are neutral or even beneficial—perhaps reflecting local positive habitat alteration or reef-effect processes in some contexts—certain physiological and behavioral outcomes remain consistently vulnerable, calling for targeted research and monitoring efforts.

Investigations into the effects of chemical pollution represent <2% of all studies and have focused on a limited and primarily commercially important taxa, such as Mytilida and Decapoda (*Mytilus edulis* and *Nephrops norvegicus*). Observed responses were often species specific: 57% of case studies reported negative impacts, whereas 43% reported no change. While *Nephrops norvegicus* and *Portunus trituberculatus* showed clear negative impacts (increased mortality and risk of injury/trauma, reduced growth, and altered behavior), *Corophium volutator* and *Mytilus edulis* exhibited no measurable effects (Figure 9; Table S1).

Electromagnetic impacts have been investigated in 24% of studies, with most experiments performed under laboratory conditions (Figure 8). Overall, 24% of studies reported negative effects on metabolism and energy budgets, navigation, other be-

haviors, and population spatial traits—primarily in crustaceans (Decapoda, such as *Cancer pagurus*) and bivalves (e.g., *Cerastoderma glaucum*) (Figure 9; Table S1). In contrast, most of the studies (74%)—many involving Pacific taxa—reported no detectable responses across the assessed species- and population-level traits (Table S1). Research on species-specific responses to electromagnetic exposure across different life stages remains insufficient, particularly for invertebrate groups with a high likelihood of exposure (e.g., sessile epifaunal and infaunal species). Moreover, it is still unclear how the specific responses observed at the individual level scale up to population- and community-level impacts,¹⁴ as most studies to date have been focused on single-species traits.

A lower proportion of studies (15%) assessed sensitivity to noise and marine traffic, covering especially crustaceans, molluscs, and echinoderms, mainly under laboratory conditions (Figure 8). Most species investigated (59%) were commercially exploited and widely distributed. For several of these species (74%)—including *Mytilus edulis*, *Loligo vulgaris*, *Doryteuthis pealeii*, *Nephrops norvegicus*, and *Sepia officinalis*—negative impacts of noise and marine traffic have been reported (increased risks of injury/trauma and mortality, changes in reproduction, energy budget/metabolism, respiration, growth, navigation, and other behaviors). In contrast, a minority of

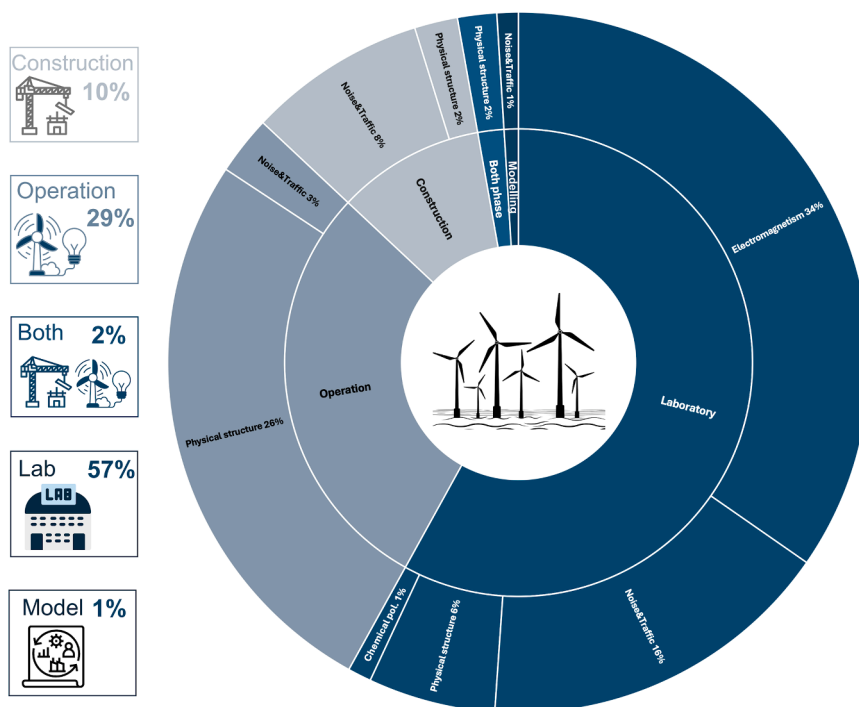


Figure 4. Percentage of case studies per type of experiment (inner ring) and exposure (external ring)

Studies representing less than 1% of the total were not included.

Vertebrates: Fish

A total of 604 case studies describing the effects of OWF-related exposures on fish were evaluated, most of which were based on laboratory experiments (Figure 8). Across all exposure types combined, negative impacts accounted for 19% of the evidence, while no-change outcomes dominated with 66%, and positive impacts represented 15% (Figure 10). This overall pattern indicates that measurable negative impacts were relatively infrequent. However, the predominance of neutral results should be interpreted cautiously, as laboratory experiments may not fully capture chronic, cumulative, or behaviorally mediated responses occurring in the field.³³

case studies found no measurable (19%) or positive responses (9%) (Figures 8 and 9; Table S1). Our results align with previous reviews highlighting the sensitivity of invertebrates to anthropogenic sound,^{40,41} particularly regarding physiological and behavioral responses in molluscs and crustaceans. However, to date, studies investigating hearing ability and the effects of anthropogenic noise have examined only a small fraction of marine invertebrate diversity. As suggested by Popper et al.³³ and Hawkins et al.,⁴¹ future research should therefore focus on a restricted number of species of commercial or conservation interest, classify them according to shared physical or physiological characteristics, and determine whether these shared traits translate into common responses to acoustic exposure from OWFs.⁸

Finally, most of the studies (59%) investigated the impacts of the physical structures of OWFs. The largest part of these studies (65%) reported positive impacts, while 14% and 21% documented negative and neutral impacts, respectively. The positive impacts referred to outcomes primarily related to community traits (diversity, richness, and abundance) and population size concerning different species of crustaceans, molluscs, and echinoderms (Figures 8 and 9). This pattern could be largely associated with the “artificial reef effect”—whereby OWF substructures create novel substrates for colonization—which has already been reported in previous studies.^{9,42–44} However, it highlights persistent and substantial knowledge gaps concerning, for example, the potential introduction of non-native species,⁸ and the consequences of shifts in benthic community composition relative to original conditions—for example, changes in trophic webs. These gaps remain relevant and should be considered a priority in future OWF impact assessments.

Chemical pollution accounted for only six case-study records, severely limiting broad inference. Half of the documented responses were negative, including injuries/trauma and behavioral changes in commercially important species such as *Collichthys lucidus* (big head croaker) and *Coilia nasus* (Japanese grenadier anchovy), whereas the remaining studies reported no changes in mortality, growth, or reproduction in *Oryzias melastigma* (rice fish) (Figures 8 and 10; Table S1). The low number of studies ($n = 6$) and investigated species ($n = 3$) likely reflects the practical challenges of tracing the ecological consequences of chemical release: chemicals disperse broadly in the water column, follow complex degradation pathways, and may generate indirect effects through bioaccumulation or biomagnification.³⁹ These constraints have also been noted in previous studies,^{6,9} which similarly reported insufficient evidence to determine general patterns of chemical impacts on marine organisms. As a result, current understanding of chemical pollution associated with OWFs remains highly uncertain.

EMFs generated by subsea cables were investigated in 49% of case studies, the vast majority of which (94%) reported neutral effects, while only 6% documented negative impacts (Figures 9 and 10). Negative responses were primarily observed in some species known to rely on electroreception or magnetic cues, as *Larimichthys crocea* (large yellow croaker), *Leucoraja erinacea* (little skate), *Gadus morhua* (Atlantic cod), *Raja clavata* (thornback ray), and *Salmo trutta* (sea trout).^{16,45,46} The predominance of neutral outcomes across species traits, such as growth, energy budget/metabolism, feeding, and behavior, as well as population- and community-level attributes, suggests that electromagnetism rarely produces strong, measurable ecological effects. For example, population size showed no change in 100% of studies, population spatial traits were neutral

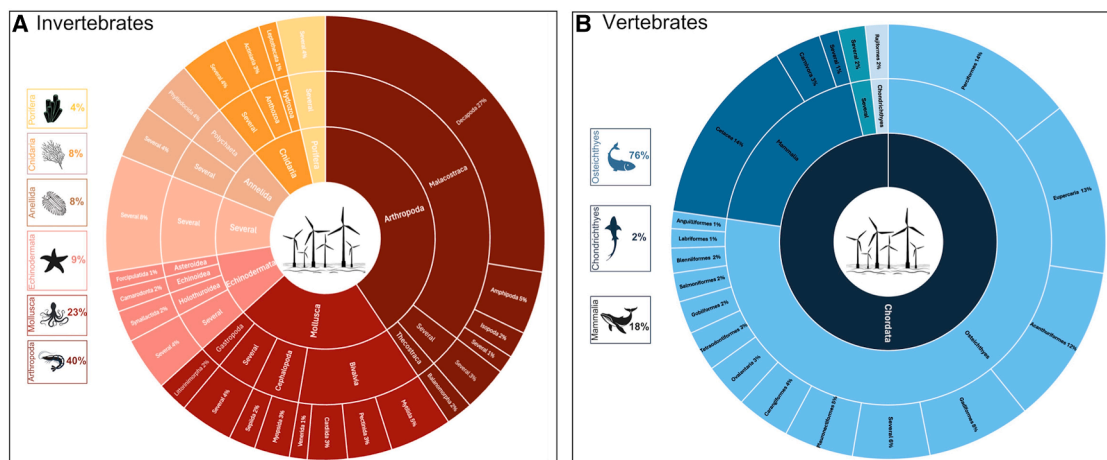


Figure 5. Percentage of case studies per taxon of invertebrates (A) and vertebrates (B)
Studies representing less than 1% of the total were not included.

in 67% of studies, and community abundance and richness were unaffected. Neutral responses were documented across 146 species, indicating broad tolerance or limited sensitivity to electromagnetic levels typical of operational OWFs. Nevertheless, the few negative outcomes observed in magneto- or electro-sensitive species highlight the need for ongoing research on other taxa whose navigation or foraging relies on these sensory modalities, especially considering electromagnetism levels associated to floating OWFs.¹⁴

Noise and marine traffic constituted the second most frequently examined exposure type (24%). Of these, 55% ($n = 81$) reported negative impacts, while 43% ($n = 63$) found no measurable change, suggesting that although many species exhibit resilience or tolerance, sound-sensitive taxa may be affected (Figures 8 and 10; Table S1). Negative impacts mainly involved behavioral traits such as feeding (75%), avoidance (86%), acoustic communication (64%), and other behavior (73%) (Figure 10). At broader ecological levels, effects were also observed on population structure (100%) and community diversity (100%). These findings are consistent with the well-established sensitivity of some fishes to anthropogenic noise, which can disrupt communication, orientation, and foraging efficiency.^{41,47} Species such as *Acanthopagrus schlegelii*, *Gadus morhua*, *Dicentrarchus labrax*, and *Larimichthys crocea* were particularly affected. Overall, noise emerges as one of the most consistently impactful OWF-related stressors for fish.

In contrast, the physical presence of turbines and associated infrastructure generated predominantly positive or neutral effects, with 57% of records reporting positive impacts, 34% reporting no change, and only 9% documenting negative outcomes (Figures 8 and 10). Positive impacts included enhanced growth, improved energy budget/metabolism, increased attraction, larger population size, expanded spatial traits, and higher community abundance (Figure 10). These responses likely reflect artificial-reef effects, with turbines providing additional structure, shelter, and food resources that facilitate aggregation or local increases in biomass.²⁶ Commercially important species such as *Gadus morhua*, *Pleuronectes platessa*, and *Trisopterus*

luscus were frequently associated with these positive outcomes (Table S1). Negative responses were mainly related to altered habitat suitability, such as avoidance (67%) in species likely sensitive to benthic disturbance, such as *Limanda limanda* (common dab) and *Leucoraja erinacea* (little skate), and reproduction (75%) (Figure 10; Table S1). Among all exposure categories, physical structure produced the highest proportion of positive impacts, highlighting the ecological significance of habitat modification around turbine foundations.

Overall, these results reveal substantial variation in fish responses to different OWF-related stressors, with noise representing the most consistently negative exposure, electromagnetism producing predominantly neutral effects, chemicals remaining insufficiently studied, and physical structures generating well-documented reef-like benefits or refuge effects for many species. Importantly, the distribution of outcomes across ecological levels indicates that most of the evidence derives from short-term species-trait or population-level assessments, underscoring the need for long-term, community-based monitoring. Such efforts are essential for evaluating the broad consequences of OWFs on marine biodiversity and ecosystem services and for informing management strategies that minimize negative impacts while potentially enhancing habitat value.

Vertebrates: Mammals

Most case studies on marine mammals ($n = 136$) were conducted during the construction and operational phases of OWFs and involved only 12 species of Carnivora and Cetacea, underscoring the very limited taxonomic extent of existing research (Figure 8). Overall, 71% of case studies documented negative impacts, 20% found no detectable change, and only 9% reported positive effects.

Among negative outcomes, the most prevalent regarded injuries/trauma, alterations in feeding behavior, avoidance or displacement, other behavioral changes, disruption of acoustic communication, and reductions in population size. In contrast, outcomes such as navigation, respiration, and population spatial traits appeared largely unaffected by OWF presence, indicating

Ecological level

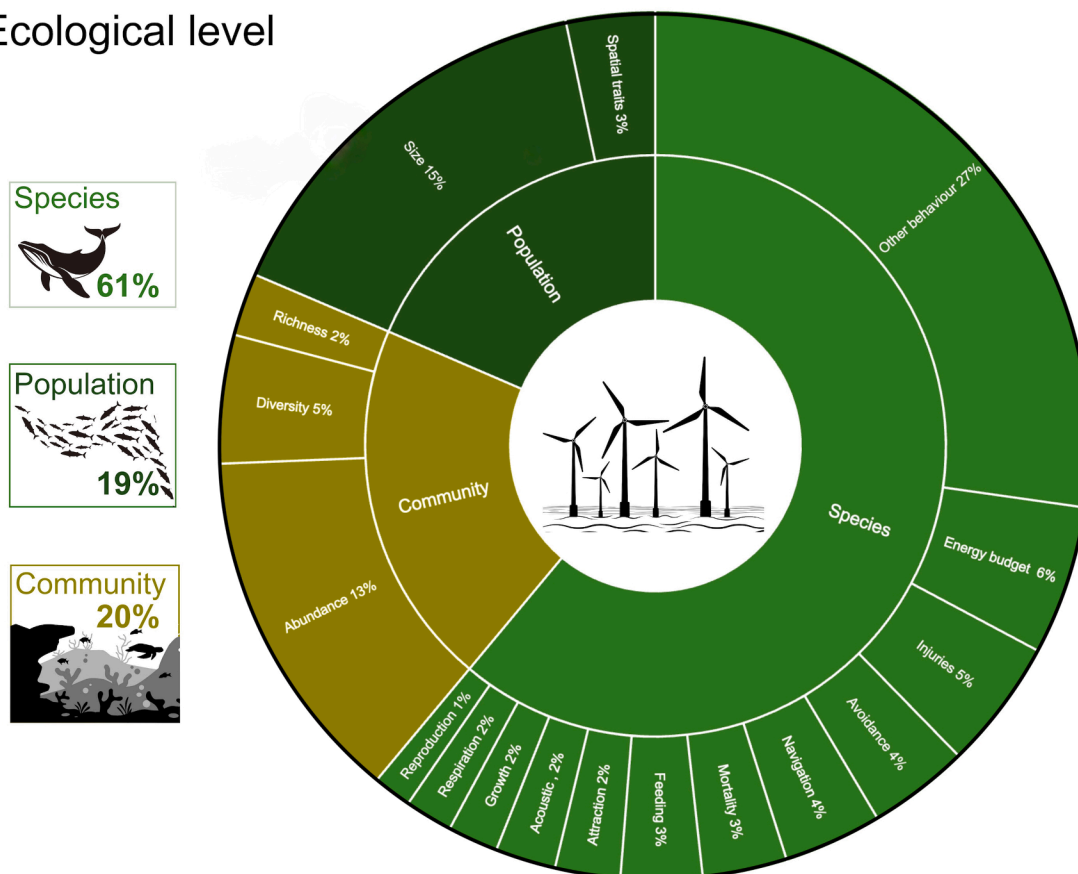


Figure 6. Percentage of case studies per ecological level and outcome
Studies representing less than 1% of the total were not included.

that not all biological functions respond uniformly across exposure contexts (Figures 8 and 11).

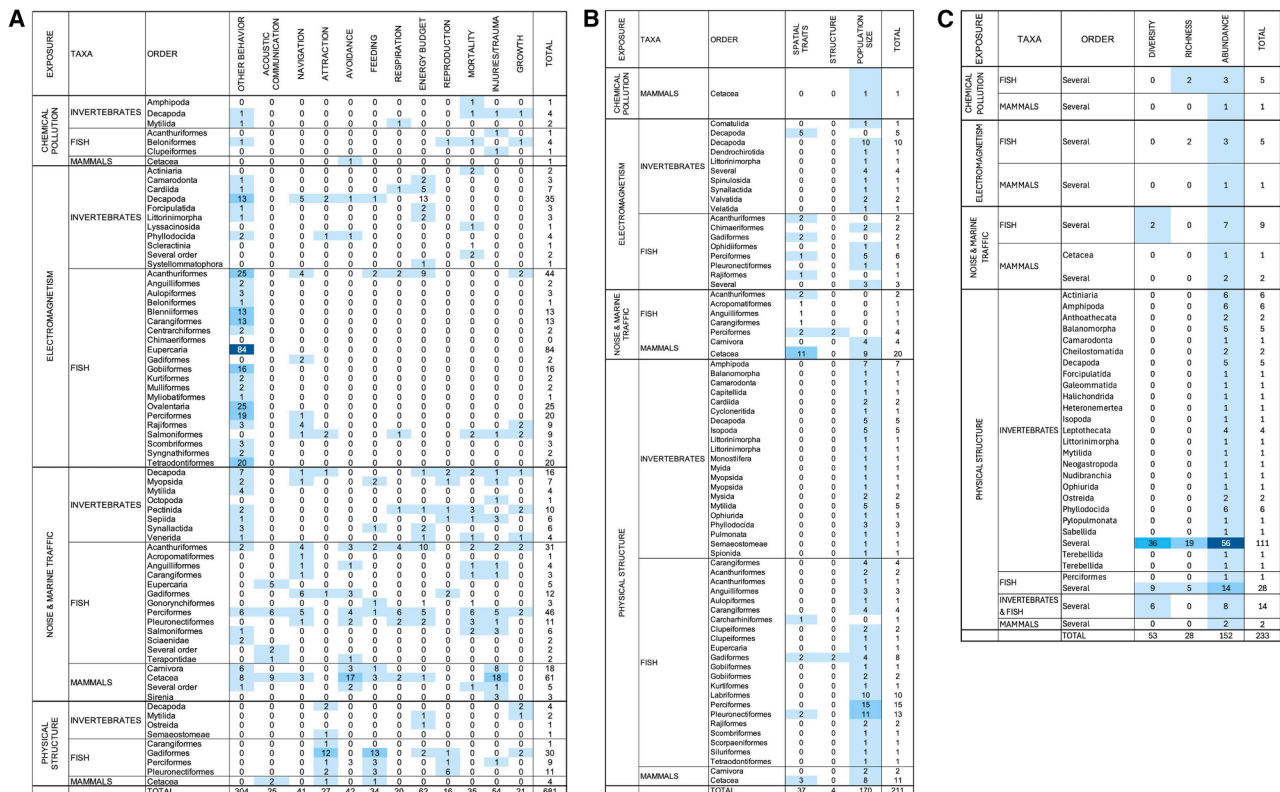
The impact of chemical pollution was assessed only for *Sousa chinensis* (Indo-Pacific humpback dolphin), a species classified as Vulnerable on the IUCN Red List (Table S1). The analysis indicated negative effects at both species and population levels. However, these results are based on only two case studies and therefore cannot be used to generalize the impact of chemical pollution on this species or similar taxa. Similarly, the impact of electromagnetism was investigated in only one study, which reported no changes at the community level.

Noise and marine traffic showed the most widespread negative effects across species and outcome categories, including injuries/trauma, feeding, avoidance, acoustic, other behaviors, population size, and community abundance (Figure 11). Among carnivores, *Phoca vitulina* (harbor seal) and *Halichoerus grypus* (gray seal) experienced predominantly negative impacts at the species level. Similarly, the cetaceans *Balaenoptera acutorostrata* (minke whale), *Delphinapterus leucas* (beluga whale), and *Tursiops truncatus* (common bottlenose dolphin) showed negative species-level responses (Table S1). Notably, *Phocoena phocoena* (harbor porpoise) exhibited the highest vulnerability, with 18 and 8 of 56 case studies reporting negative impacts at the

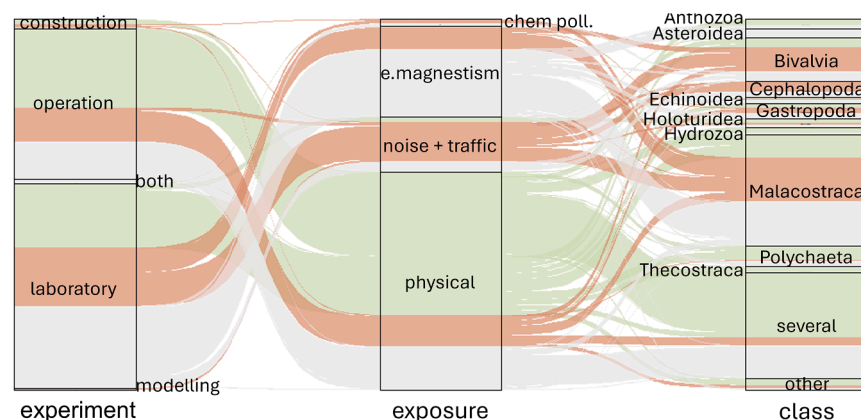
species and population levels, respectively (Table S1). With few exceptions showing limited positive responses, the overall trend indicates substantial risk from noise and marine traffic associated with OWFs.

These findings are consistent with extensive evidence that marine mammals—especially small odontocetes and pinnipeds—are highly vulnerable to impulsive noise generated during pile driving and to the chronic noise and disturbance associated with vessel traffic.^{31,32,48}

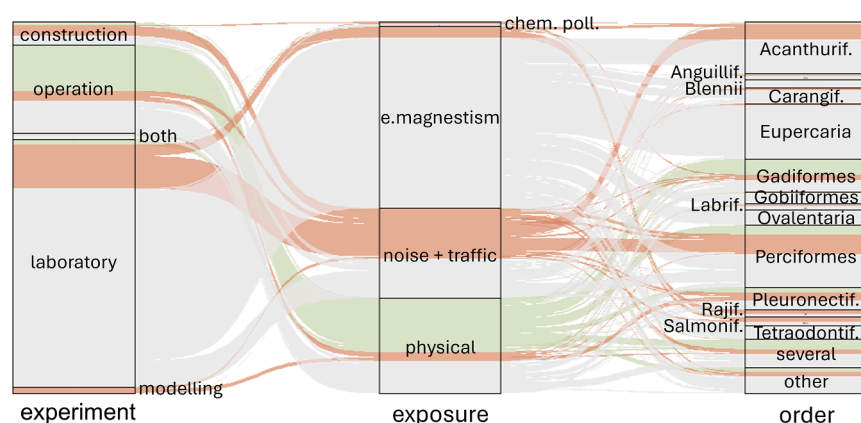
The physical presence of OWF structures produced mixed responses. Positive impacts were observed for species such as *Halichoerus grypus*, *Phoca vitulina*, and *Phocoena phocoena*, suggesting potential benefits such as habitat provision or changes in local prey dynamics, as indicated by positive impacts in outcomes such as community abundance, attraction, and feeding (Table S1). These patterns suggest that turbine foundations may create novel structural habitat—offering refuge, altered prey dynamics, or less human pressure (e.g., reduced fishing)—somewhat analogous to the “artificial reef” and “refuge effect” documented for benthic and fish communities. At the same time, negative or neutral impacts were recorded for *Phocoena phocoena* in certain regions, reflecting species-specific sensitivity to habitat alteration (Table S1). Overall, the data



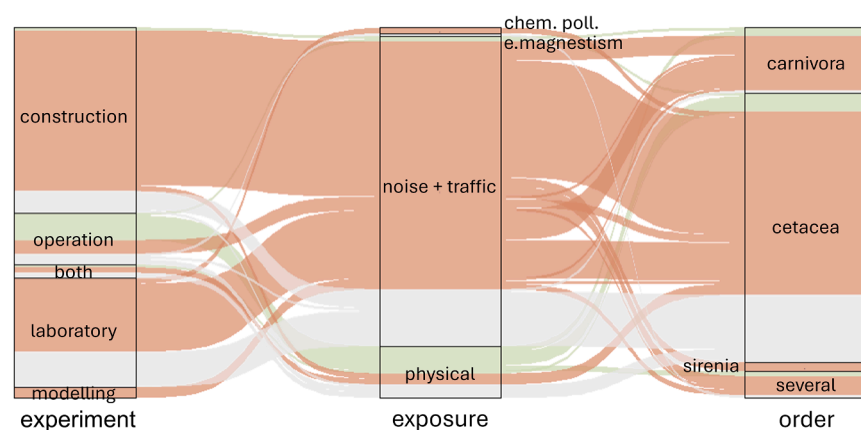
A Invertebrates



B Fish



C Mammals



■ Negative ■ Positive ■ No change

Figure 8. Alluvial plots

The plots show the relationship between the output direction (negative in red, positive in green, and no change in gray), the type of experiment, the type of exposure, and the order for (A) invertebrates, (B) fish, and (C) mammals. In this analysis, case studies representing less than 1% of the total were not included. chem.poll., chemical pollution; e.magnetism, electromagnetism; f, formes.

most uniform ISs across species, whereas the physical structure of OWFs produced low ISs. Chemical pollution obtained a high IS in the only mammal species investigated (*Sousa chinensis*). Together, these results highlight noise and marine traffic as the stressors associated with the highest biological impact across species (Figure 12; Table S2).

Overall, this synthesis highlights the importance of integrating species traits, conservation status, and evidence quality when evaluating the ecological consequences of OWFs. The taxon-specific profiles derived here provide a structured basis for prioritizing mitigation strategies and directing future data collection toward the most vulnerable species and the stressors most likely to produce biologically meaningful impacts.

Conclusion

This systematic review—encompassing 221 documents and 1,119 case studies published until June 2025—provides the most updated, comprehensive, and taxonomically inclusive synthesis to date on the ecological impacts of OWFs on marine fauna. Three main conclusions emerge from the analysis.

First, the current evidence base is highly uneven across geographic areas, taxa, exposure types, and ecological levels. Research has been over concentrated in the North Sea and adjacent North European waters, with comparatively limited representation from rapidly expanding OWF regions such as Asia. Fish and invertebrates dominate the literature, while marine mammals—despite they may seem to be the most vulnerable—remain comparatively understudied.

Second, the magnitude and direction of OWF impacts vary strongly among exposure types, taxa, ecological levels, and biological outcomes. Across all species, nearly half of the studies reported no measurable effects. Invertebrates displayed

although most species displayed moderate to high ISs under noise and marine traffic and chemical pollution (Figure 12; Table S2). A more consistent pattern was found for mammals: noise and marine traffic exposure generated the highest and

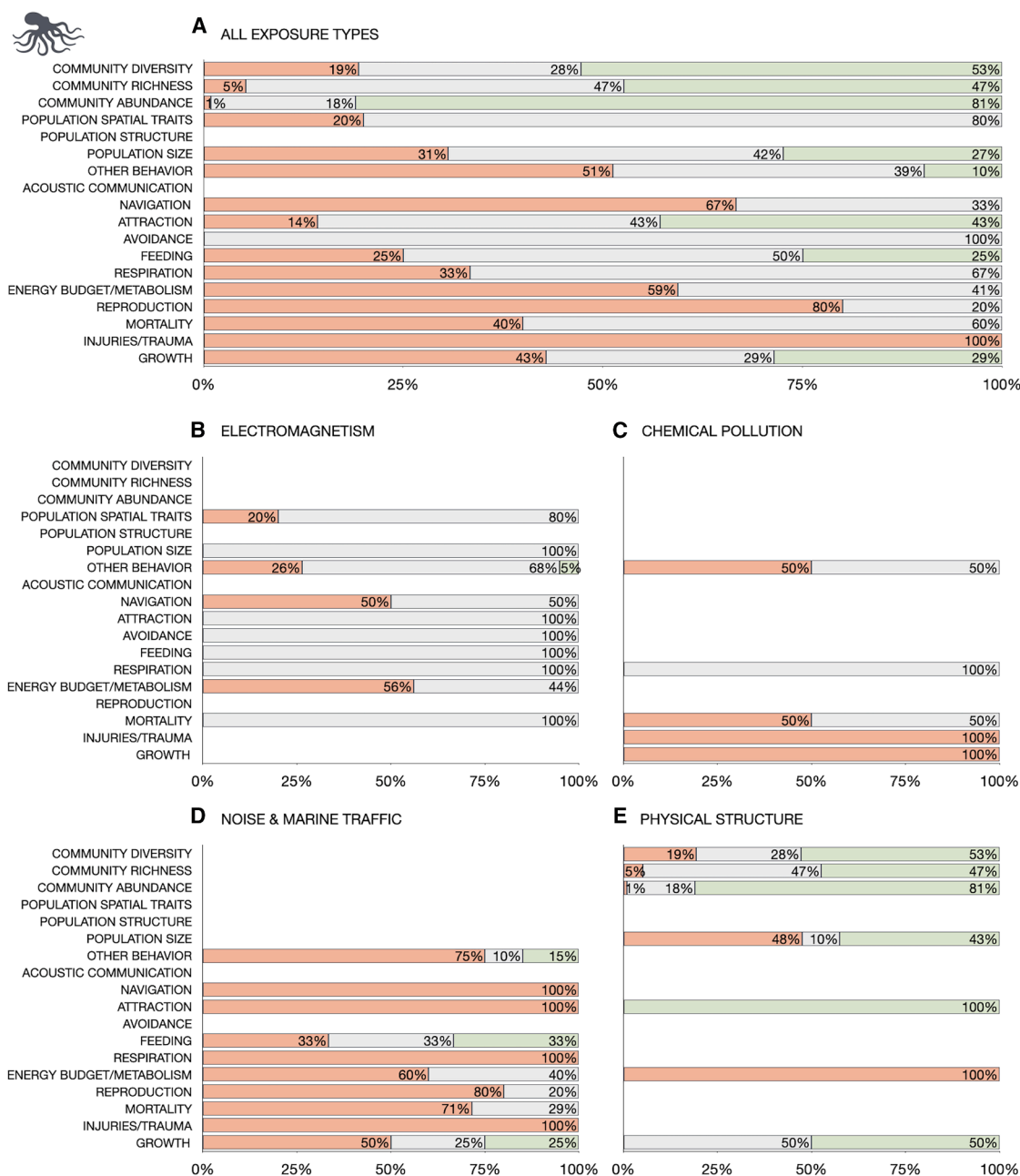


Figure 9. Percentage of case studies concerning invertebrates detailed per exposure type, outcome, and impact (negative in red, no change in gray, and positive in green)

A = all exposure types; B = electromagnetism; C = chemical pollution; D = noise and marine traffic; E = physical structure.

predominantly positive responses, largely driven by structural reef-effect processes, although specific functional traits, such as metabolism, reproduction, and behavior, emerged as consistently vulnerable. In fish, electromagnetism produced predominantly neutral responses, while noise and marine traffic yielded the most frequent negative outcomes, especially in behaviorally mediated traits. Marine mammals exhibited the highest proportion of negative impacts, attributable primarily to noise. Positive impacts from turbine structures appeared localized and species

specific. These patterns emphasize that noise and marine traffic are the most consistently detrimental OWF-related stressors across marine vertebrates, whereas structural habitat alteration produces a more heterogeneous range of effects, from beneficial aggregation to local displacement.

Third, the IS, developed in this review, reveals clear taxon-specific vulnerability profiles and highlights the importance of integrating species susceptibility with conservation status, biogeographic range, and evidence reliability. This framework,

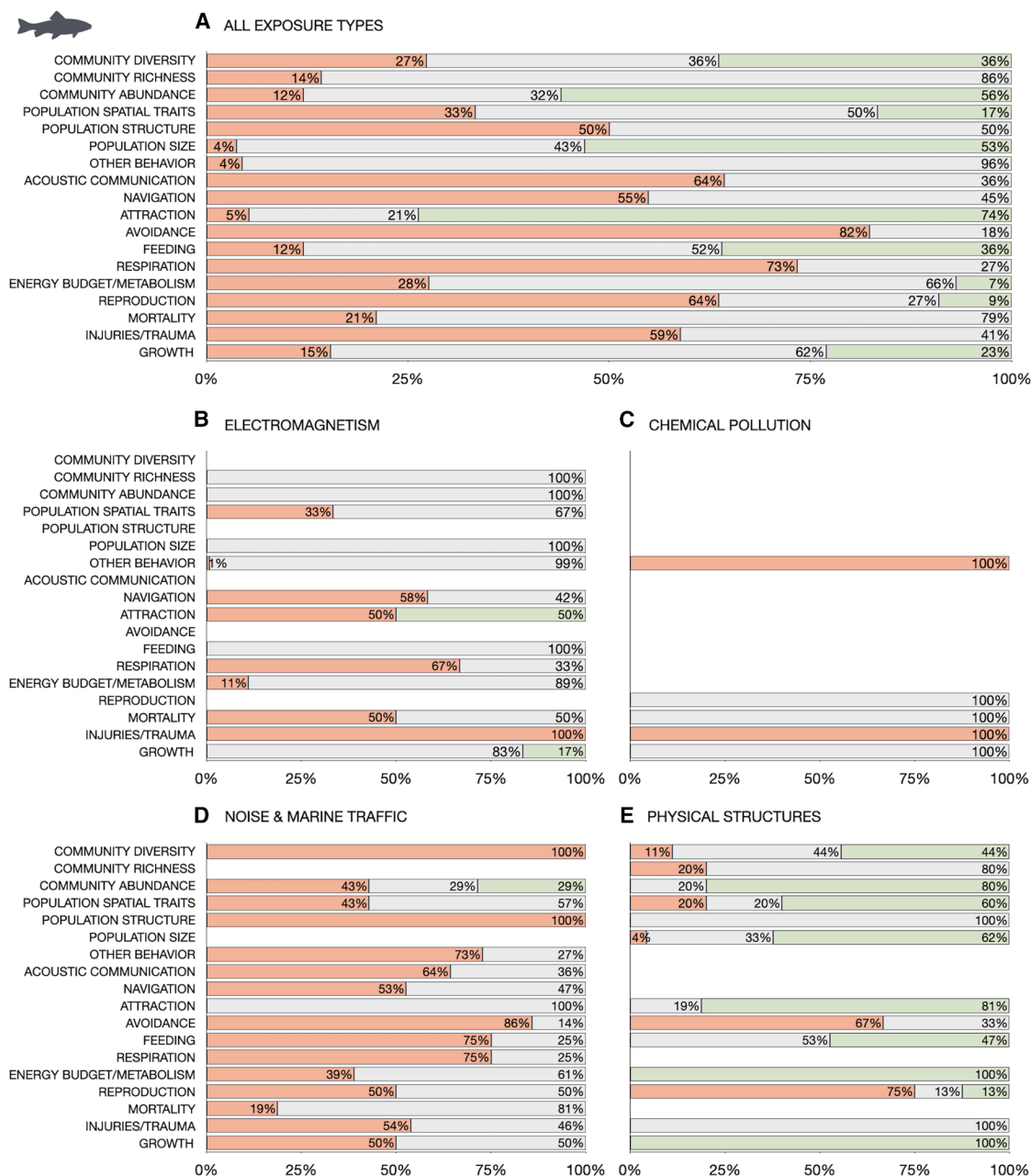


Figure 10. Percentage of case studies concerning fish detailed per exposure type, outcome, and impact (negative in red, no change in gray, and positive in green)

A = all exposure types; B = electromagnetism; C = chemical pollution; D = noise and marine traffic; E = physical structure.

although it cannot capture finer-scale habitat specialization or regional population dynamics, provides a transparent, comparative tool for estimating potential species-level risk in multispecies assessments where standardized effect sizes are unavailable. Notably, the highest and most uniform ISs under noise and marine traffic were found for mammals, while low scores were displayed for fish except under noise, and invertebrates spanned the widest score range. Such information establishes a foundation for identifying species that should be priori-

tized in future research, using existing knowledge from other regions to verify—or refute—the impacts associated with OWFs installed in different geographic contexts. Thus, the approach is scalable, adaptable, and well suited to emerging OWF regions lacking baseline ecological data.

Taken together, these results indicate that OWFs can generate both ecological opportunities and risks, but the magnitude and direction of impacts depend heavily on species traits, ecology, local environmental conditions, and technological choices (e.g.,

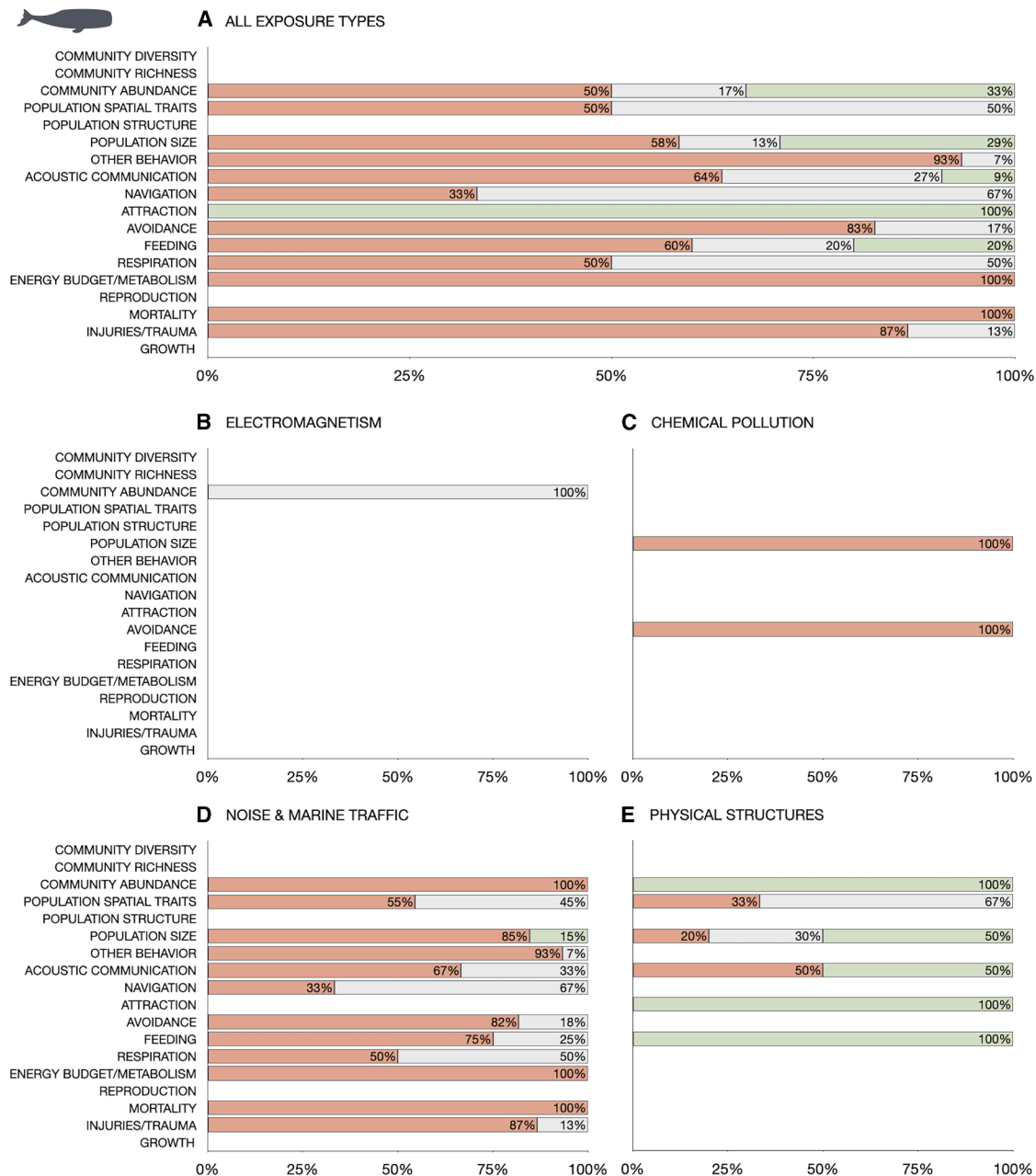


Figure 11. Percentage of case studies concerning mammals detailed per exposure type, outcome, and impact (negative in red, no change in gray, and positive in green)

A = all exposure types; B = electromagnetism; C = chemical pollution; D = noise and marine traffic; E = physical structure.

foundation type, cable configuration, and spatial layout). Nevertheless, as OWF capacity expands globally—and floating wind technology extends development into deeper offshore ecosystems—understanding the interplay between these factors becomes critical. Results, however, derive from a variety of designs, scales, metrics, and analytical approaches, where laboratory experiments dominate the dataset and field studies often lack standardization, consistent baselines, or rigorous controls, thereby complicating cross-study comparisons. Therefore, from a man-

agement perspective, these findings call for a strategic shift from patchy, short-term assessments to integrated, long-term in-field monitoring programs that explicitly address cumulative, synergistic, and temporally dynamic impacts (Table 2). In fact, there is an urgent need to shift from single-stressor studies to assessing cumulative and synergistic impacts, capturing how co-occurring pressures interact in real-world scenarios. Concurrently, monitoring must scale up from short-term, species-specific traits toward long-term ecosystem responses to track multi-scale

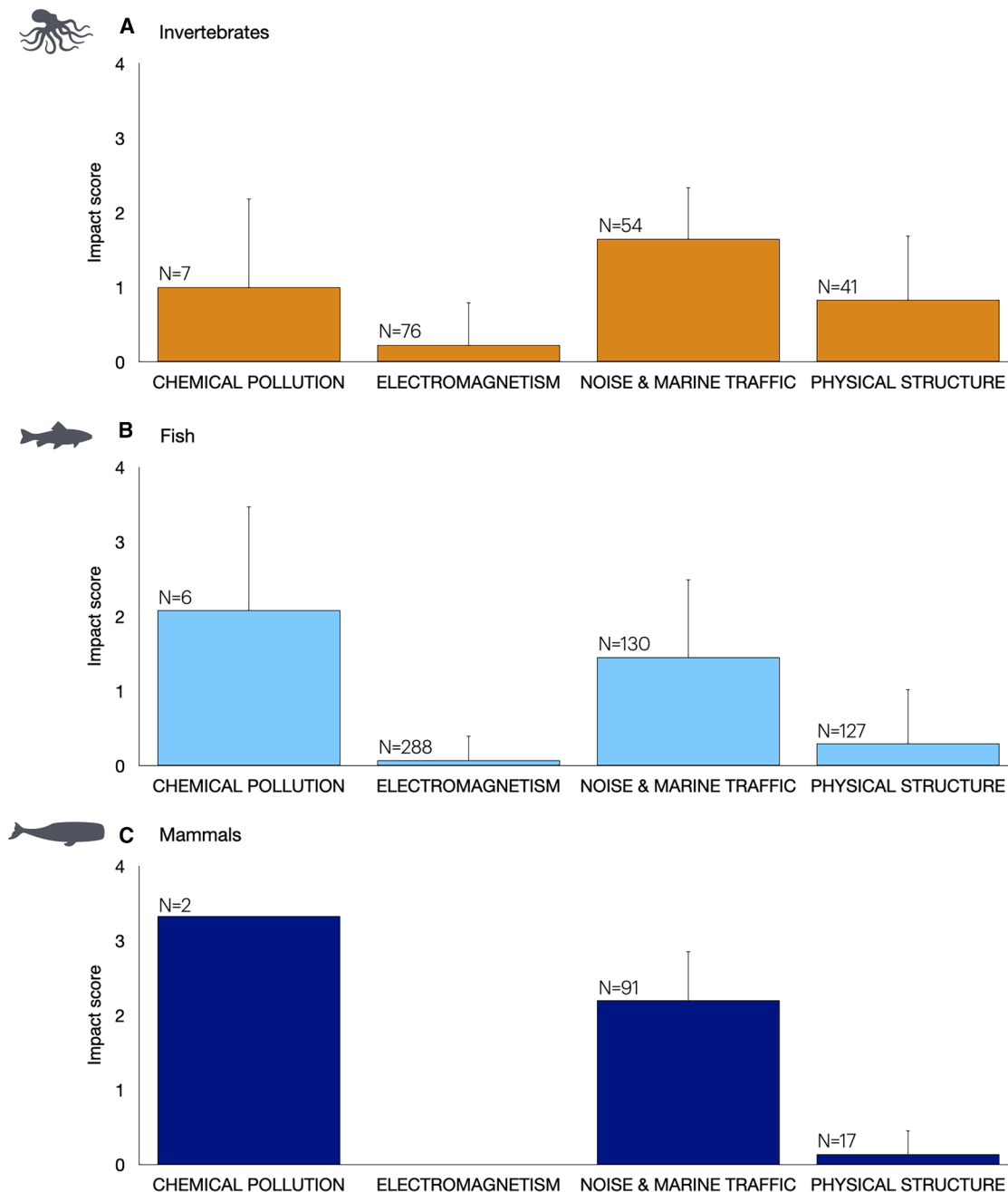


Figure 12. Mean (±SD) impact score detailed per taxa and exposure

A = invertebrates; B = fish; C = mammals. "N" indicates the number of case studies used to calculate the impact score.

alterations from individuals to populations and community levels. Moreover, as the industry expands into deeper waters, future research must prioritize evaluating the impacts associated with emerging floating offshore wind technologies.

By revealing both the strengths and gaps in the most updated current knowledge base so far, this review provides a foundation for guiding future research to ensure that offshore wind contributes to climate goals without compromising marine ecosystem integrity.

STUDY LIMITATIONS

Although the systematic review was conducted rigorously and in accordance with established protocols, some limitations should be highlighted. First, the restriction to English-language publications may have led to the exclusion of relevant studies from rapidly expanding OWF regions such as China, Japan, Taiwan, South Korea, and parts of South America, potentially limiting the global representativeness of the dataset. In addition, the

Table 2. Synthesis of the review results from a monitoring and management point of view

Theme	Evidence from review	Management recommendation
1. Noise & marine traffic	most consistently negative impacts for fish and mammals; sublethal and behavioral disruptions common	● implement noise-reduction technologies ● schedule construction outside sensitive periods (breeding and migration) ● enforce vessel-speed restrictions and minimize traffic in key habitats
2. Physical structures	frequent positive impacts (reef/refuge effects), but potential for non-native species introduction and trophic shifts	● design turbine foundations to maximize habitat value where beneficial ● monitor colonization dynamics and community shifts ● implement biosecurity measures to reduce non-native species spread
3. Electromagnetism (EMF)	predominantly neutral impacts; some species-specific vulnerabilities	● prioritize EMF monitoring for electro/magneto-sensitive species ● evaluate EMF intensities expected from floating wind technologies
4. Chemical pollution	very limited evidence; some negative impacts in a few taxa	● strengthen leak-prevention protocols and sediment-disturbance controls ● monitor contaminant pathways during cable laying and maintenance
5. Taxonomic & geographic biases	overrepresentation of European shelf systems; underrepresentation of mammals and global regions	● expand monitoring to Asia, North America, and other OWF-expanding regions ● prioritize long-lived, threatened, and wide-ranging species
6. Ecological levels	most studies short-term and species-trait focused; few population/community assessments	● implement long-term, multi-scale monitoring (individual → population → community) ● use standardized methodologies to reduce inconsistencies among studies
7. Cumulative & synergistic effects	rarely assessed despite real-world co-occurrence of stressors	● coordinated monitoring to capture multi-stressor interactions
8. Impact score (IS)	novel approach enabling cross-taxon, multispecies comparisons	● use IS to prioritize monitoring and mitigation for species with high susceptibility and conservation concern

exclusion of gray literature (e.g., governmental reports, environmental impact assessments, and industry monitoring documents) may have further constrained the comprehensiveness of the evidence base.

A clear spatial imbalance emerged, with a strong concentration of studies conducted in the North Sea region, while other geographic areas remain comparatively underrepresented. Furthermore, most available studies focus on short-term, species-level responses—often derived from controlled laboratory experiments or short monitoring programs—while long-term, population- and community-level assessments remain scarce. Consequently, the ability to infer long-term, cumulative, or ecosystem-scale effects remains limited, particularly for long-lived and highly mobile species.

Finally, the high degree of methodological and analytical heterogeneity across the reviewed literature—including differences in study design, sampling strategies, spatial and temporal scales, and response variables—did not allow for the derivation of standardized and comparable effect sizes. This lack of methodological consistency precluded the implementation of a robust and statistically sound quantitative meta-analysis.

METHODOLOGY

The review process started by formulating the central research question (“What is the impact of offshore wind farms on marine biodiversity?”), following the methodological framework outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.^{49–51} Based on this question, three specific search strings were developed: (1) (“wind farm” OR “pile driv*” OR “wind power”) AND (benth* OR bryoz* OR sponge* OR crustacea* OR mollusc* OR coral* OR echinoderm* OR polychaet* OR tunicat* OR worm); (2) (“wind farm” OR “pile driv*” OR “wind power”) AND (fish OR fisher* OR megafauna OR pelagic); (3) (“wind farm” OR “pile driv*” OR “wind power”) AND (“marine mammal*” OR cetacean OR *whale* OR *dolphin* OR porpoise* OR megafauna OR pelagic). The review team collaboratively developed the search strings through an iterative process that involved identifying key terms from preliminary readings of existing reviews in the field and testing various keyword combinations across databases to assess their sensitivity and specificity. The study investigated underwater pressures on marine fauna only and, therefore, the literature search did not include impacts on organisms such as seabirds (which are affected by above-surface pressures) or

phytoplanktonic organisms. Relevant literature was retrieved through systematic searches in major academic databases, namely, Scopus and Web of Science, and on Tethys (<https://tethys.pnnl.gov>), an online knowledge management system that provides information and scientific literature on the environmental effects of wind farms and marine renewable energy. We focused on peer-reviewed articles and conference proceedings published in English up to June 2025. Gray literature sources—mainly environmental impact assessment reports—were excluded because they are either not peer reviewed, not publicly accessible, or not available in English.^{28,52} This strategy ensures consistency in the methodological quality and reliability of the included studies.

sults even within the same species, conducting a meta-analysis may not be appropriate.⁵⁴ Thus, data were analyzed through a combination of qualitative and semi-quantitative methods, relying on counts and percentage frequencies of documents and case studies. Geographic patterns were visualized using a map generated in QGIS (version 3.16.3). The alluvial diagram was produced in R⁵⁵ using the ggalluvial package.⁵⁶

Then, to quantify the potential negative impacts of each exposure type on marine taxa, an IS was calculated for each species by integrating species susceptibility, distribution, conservation status, and evidence reliability, as follows:

$$IS = \text{Species Susceptibility} \times \frac{(\text{Distribution Score} + \text{Conservation Status Score} + \text{Reliability Score})}{3}$$

Following data export from web search engines, duplicates were removed, and an initial title and abstract screening was conducted to exclude studies outside the inclusion criteria (Table 2), according to the PECO framework.⁵³ Two reviewers independently conducted the screening process, and quality assurance was maintained through cross-checking: a subset of articles reviewed by one reviewer was re-evaluated by the other. Any disagreements were resolved by a third author (G.L.M.). The full-text screening of the selected articles was done following the same inclusion/exclusion criteria and quality verification process. If a document addressed multiple taxonomic groups, exposure types, or presented several outcomes, each was treated as an individual case study. For every case study included, the following information was extracted and recorded in an Excel database: (1) general bibliographic details (title, journal, authorship, and publication year); (2) contextual and methodological data (e.g., whether the study was conducted during construction and/or operational phases, laboratory setting, or model predictions; country and coordinates; study area size in km²; and duration in days); (3) taxonomic details of the species involved (phylum, class, order, and species); and (4) information on exposure types, measured outcomes (as described in Table 1), and the related direction of impact. Impact was defined as a biologically significant effect that reflects a change sufficient to have consequences for individuals, populations, and communities.⁴⁷ Such impacts can have two potential directions—positive or negative—as well as a neutral direction, indicating no change in outcomes.

Complementary to the inclusion criteria, the following exclusion criteria were used: (1) studies on freshwater animals, (2) studies having no wildlife as the main subject (e.g., studies on humans), (3) studies using socio-economic response variables, and (4) studies related to engineering techniques.

Due to substantial variability and inconsistency in the methods and metrics used to assess ecological effects of OWFs across the reviewed studies, a formal statistical meta-analysis was not feasible. Further, since the results of apparently similar studies are reporting widely different re-

Similar composite indices have already been used in conservation science^{57–59} and are particularly valuable in multispecies assessments where data availability and quality vary, making formal meta-analysis unfeasible. Species susceptibility was estimated as the proportion of studies reporting negative impacts relative to the total number of studies available for that species. This approach is consistent with widely used vote-counting and evidence-frequency methods applied when studies differ in design and metrics or lack comparable effect sizes. This type of synthesis has been widely used in human-impact assessments, including wind-farm impact studies,^{59–61} especially when research designs are too heterogeneous to permit formal meta-analysis. Large-scale species distribution was assessed based on the number of oceans where a species occurs (derived from IUCN lists): (1) presence in five oceans = 1; (2) presence in four oceans = 2; (3) presence in three oceans = 3; (4) presence in two oceans = 4; and (5) presence in one ocean = 5. The number of oceans occupied provides a coarse but ecologically meaningful proxy for global geographic range size. Species distributed across multiple ocean basins typically exhibit broad environmental tolerances, widespread dispersal capabilities, and consequently larger overall ranges. In contrast, species confined to a single ocean generally have more restricted ranges and fewer opportunities for dispersal, making them more vulnerable to regional threats. This approach aligns with long-established findings that narrow geographic ranges strongly predict extinction risk across taxa. Using ocean presence data derived from standardized IUCN range maps avoids subjective judgments about what constitutes “small” or “large” geographic ranges, ensuring consistency across taxa and facilitating comparison among species with widely differing biogeographic patterns. Finally, this categorical approach is appropriate for large-scale, multi-species assessments, where fine-resolution range metrics may be unavailable, inconsistent, or unnecessarily complex. The conservation status score is a numeric value assigned to each IUCN conservation status (Reid et al.): (1) Not Evaluated (NE) or Data Deficient (DD) = 0; (2) Least Concern (LC) = 1; (3)

Near Threatened (NT) = 2; (4) Vulnerable (VU) = 3; (5) Endangered (EN) = 4; and (6) Critically Endangered (CE) = 5.

Evidence reliability was scored as follows (Watson et al.): (1) 1 study = 1; (2) 2–5 studies = 2; (3) 6–10 studies = 3; (4) 11–20 studies = 4; and (5) more than 20 studies = 5. Using study count as a proxy for reliability reflects widely accepted principles in evidence evaluation: the strength of inference generally increases with the volume, consistency, and independence of available evidence.

The multiplicative structure of the IS ensures that species experiencing both high susceptibility and high conservation concern receive appropriately elevated scores.

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AUTHOR CONTRIBUTIONS

G.L.M., writing – original draft, formal analysis, data curation, and conceptualization; M.M.M., A.C., and A.P., writing – original draft, methodology, formal analysis, and data curation; G.C., writing – original draft, project administration, investigation, funding acquisition, and conceptualization.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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