Impacts of offshore wind farm expansion: what are the consequences for achieving Good Environmental Status across European marine waters?

A report of the Eklipse Expert Group on Impacts of Offshore Wind Farm Expansion

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October 2025

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bioagora

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Abbreviations

ABBREVIATIONS

ACRONYM	DESCRIPTION
ABI	The Bay of Biscay and the Iberian Coast
ACS	Celtic Seas
After only	Collection of data after the installation of a wind farm
AMA	Macaronesia
ANS	The Greater North Sea, including the Kattegat and the English Channel
BA	Before-After (temporal comparison)
BACI	Before-After-Control-Impact
BAL	Baltic Sea
BLK	Black Sea
CI	Control-Impact (reference site or site comparison)
D (e.g. D1, D2, D3 etc)	Descriptor
DG-ENV	Directorate General for Environment
DPSIR	Driver-Pressure-State-Impact-Response Framework
EEA	European Environment Agency
EEZ	Exclusive Economic Zone
EU	European Union
EUNIS	European Nature Information System
EC	European Commission
EWG	Expert Working Group
GBF	Gravity-Based-Foundation
GES	Good Environmental Status
GW	Gigawatt
ICES	International Council for the Exploration of the Sea
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
KCB	Knowledge Coordination Body
LOBE	Level of Onset of Biological
MAD	The Adriatic Sea
MAL	The Aegean-Levantine Sea
MEG	Methods Expert Group
MIC	The Ionian Sea and the Central Mediterranean Sea
MPA	Marine Protected Area
MSFD	Marine Strategy Framework Directive
MWE	Western Mediterranean Sea
NIS	Non-Indigenous Species
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine
PerSPEcTiF	Perspective, Setting, Phenomenon of interest, Environment, Timing, Findings
SSB	Spawning Stock Biomass
SPM	Suspended Particulate Matter
SR	Scoping Review
SSS	Short Science Summary
UK	United Kingdom
UXO	Unexploded Ordnance
WOSCC	Web of Science Core Collection

Glossary

GLOSSARY

A priori protocol: A predefined plan or procedure established before conducting a knowledge synthesis, ensuring transparency, consistency, and replicability in the research process.

After-Only design: A study design that samples only after an intervention or impact has occurred, often at multiple time points. Lacks baseline data and controls, limiting its ability to make causal inferences.

Barotrauma: Physical injuries caused by sudden changes in pressure, particularly affecting air-filled or gas-regulating organs in animals. In the context of OWFs, barotrauma is especially relevant during construction activities such as pile driving and seismic surveys, which generate underwater impulsive sound waves and pressure changes.

Before-After (BA): A temporal comparison at a single site, assessing conditions before and after an intervention or impact. No control site is used, which limits the ability to isolate the effect from natural variability.

Before-After-Control-Impact (BACI): A robust study design combining both temporal (before/after) and spatial (control/impact) comparisons. It helps distinguish real impacts from natural changes over time or space.

Cellular Energy Allocation (CEA): A physiological measure quantifying how organisms allocate energy resources at the cellular level among key biological processes: growth, reproduction, maintenance, and stress response. The key components of CEA are Energy Available (Ea): total energy obtained from food (e.g., carbohydrates, lipids, proteins); Energy Consumed (Ec): energy expended for maintenance (respiration, cellular repair) and stress responses (detoxification, heat shock proteins), and the Net Energy allocation (NE): energy left for growth/reproduction.

Collision risk: Likelihood that animals, particularly flying species such as birds and bats, will physically collide with wind turbine blades or other OWF infrastructure (e.g., towers, substations) during flight.

Control-Impact (CI): A study design that compares conditions at an impacted site (e.g., with an Offshore Wind Farm, OWF) and a control site (without the impact), typically at the same point in time. It helps identify spatial differences, potentially due to the impact.

Cumulative impacts: Impacts (positive or negative, direct or indirect, short-term or long-term) resulting from multiple activities within a region or area. These effects may be negligible when considered individually, but can become significant when combined, especially over time. They encompass the influence of past, present, and reasonably foreseeable future actions on the environment.

Decommissioning: The process of removing offshore structures, such as wind turbines and foundations, at the end of their operational life, ensuring minimal environmental disturbance and compliance with MSFD-related environmental standards.

Ecosystem efficiency: It refers to how effectively an ecosystem converts energy—typically from primary production—into biomass across trophic levels, recycles nutrients, and sustains ecological functions. It is commonly measured using Trophic Transfer Efficiency (TTE), defined as the percentage (%) of energy or biomass transferred from one trophic level to the next, and biomass ratios (e.g., predator: prey), which reflect the relative biomass across trophic levels. These are often expressed in units like $kcal/m^2/yr$ or $gC/m^2/yr$.

Electromagnetic radiation or electromagnetic fields: Waves of electric and magnetic energy moving through space. With OWFs, the most relevant type is non-ionising electromagnetic fields generated by subsea power cables.

Environmental impacts: The effects resulting from human activities on marine environments, including alterations to seabed integrity, underwater noise, contamination levels, and changes in species abundance or distribution. Under the MSFD, impacts are assessed in relation to descriptors that define GES.

European Commission's Directorate-General for Environment (DG ENV): The department within the European Commission responsible for EU policies and actions related to environmental protection, including the implementation of the MSFD and the development of policies aimed at achieving GES in marine environments.

Eutrophication: The process by which a body of water becomes enriched with excess nutrients (mainly nitrogen and phosphorus), often due to runoff from land or human activities, leading to excessive growth of algae and other aquatic plants.

Fixed-bottom Wind Farms: Offshore wind parks with foundations anchored to the seabed, typically suitable for shallow to mid-depth waters.

Good Environmental Status (GES): A condition in which marine ecosystems are healthy, resilient, and productive, and the use of marine resources is sustainable. Achieving GES is the primary objective of the MSFD, with specific descriptors and threshold values set by EU Member States to measure progress.

Gradient Sampling Design: Sampling is conducted along a spatial or temporal gradient of impact (e.g., distance from an OWF). Useful for detecting change intensity and response thresholds.

Habitat suitability: Degree to which a specific environment or area provides the necessary conditions to support the survival, growth, and reproduction of a particular species or community.

Impact: The effect of pressure on the ecosystem, either on abiotic (non-living parts of habitats) or biotic ones (organisms). Impacts refer to the consequences for the ecosystem in terms of changes to specific ecosystem features.

Keystoneness index: A quantitative metric used in ecological network analysis to assess how crucial a particular species (or functional group) is to the structure and functioning of an ecosystem. It indicates the degree to which a species acts as a keystone species, i.e., one whose influence on the ecosystem is disproportionately large relative to its abundance or biomass.

Knowledge gap: A specific subject or topic within a body of research where empirical evidence/data is lacking to draw reliable conclusions. In evidence synthesis, gaps refer to areas where little or no individual/primary studies exist that cover a similar question/test a similar hypothesis.

Level of Onset of Adverse Biological Effects (LOBE): A sound level above which adverse biological effects are expected to occur in indicator species, i.e., an effect that may affect the comfort, survival, and vital functions of individual animals.

Marine Strategy Framework Directive (MSFD): An EU directive aimed at protecting and preserving the marine environment by establishing a framework for the achievement of GES across European seas. It requires Member States to assess their marine ecosystems, set environmental targets, and implement programs of measures.

MSFD Descriptor: A specific element or aspect of the marine environment as defined under the MSFD, used to assess the ecological or environmental status of European waters.

Offshore Wind Farm (OWF): Collection of offshore wind turbine generators that produce electricity by harnessing wind energy at sea. They include two main types: fixed-bottom foundations, which are suitable for shallow waters, and floating foundations, designed for use in deeper waters.

Marine Ecosystems: Complex communities of marine organisms and their physical environment that are interconnected and function as a whole. The MSFD emphasises maintaining the health and resilience of these ecosystems to achieve GES.

Maximum Sustainable Yield (MSY): It is the largest long-term average catch (or harvest) of a species that can be taken from a fishery stock without causing population decline, ensuring the stock remains sustainable over time.

Non-indigenous species: Also known as non-native, alien, or introduced species. These are organisms that have been found outside their natural geographic range due to human activity, whether intentionally or unintentionally. OWF structures (such as turbine foundations, cables, and platforms) can provide artificial hard substrates in marine environments, which may be colonised by a wide variety of marine organisms, including NIS.

No Comparator: A study design that does not include a baseline or control group, often descriptive or exploratory in nature. Interpretation of cause-and-effect relationships is limited.

Participatory workshop: An interactive meeting involving experts and stakeholders to discuss findings, fill knowledge gaps, and develop insights related to marine environmental management.

Physical loss of habitat: Extreme pressure on marine ecosystems occurs when the substrate, morphology, or topography is permanently altered.

Physical disturbance: Human-induced changes to the physical structure and properties of the seafloor that can be reversed if the disturbing activity ceases.

Photic limit (or euphotic zone depth): It refers to the maximum depth in the water column where sunlight penetrates sufficiently to allow photosynthesis by aquatic plants and phytoplankton.

Pile driving: Construction method used in the installation of offshore wind turbine foundations, especially in fixed-bottom OWFs. It involves driving large piles into the seabed to secure turbine structures, substations, or other infrastructure. Different pile driving methods include impact and vibratory.

Policy-relevant knowledge: Information produced through scientific research, assessments, and scenario modelling that directly informs marine policy development and the implementation of measures to achieve or maintain GES under the MSFD.

Predicted No Effect Concentration (PNEC): Threshold concentration of a chemical (e.g., pollutant, contaminant) below which no adverse effects are expected on organisms or ecosystems.

Pressure: The mechanism through which an activity affects any part of an ecosystem.

Primary production: Process by which autotrophic organisms (mainly phytoplankton, algae, and seagrasses) convert inorganic carbon (CO_2) into organic compounds using sunlight (photosynthesis). This process forms the base of the marine food web.

Scenario modelling: A method used to simulate and compare different possible future conditions based on varying assumptions. It is commonly applied in environmental and ecological systems to support decision-making under uncertainty, including in the context of the MSFD. Typical modelling approaches include: **1**) Ecopath with Ecosim (EwE): A mass-balance food web model used to simulate trophic interactions and ecosystem dynamics. **2**) Hydrodynamic–Ecological Coupled Models: Integrated models that simulate physical ocean processes alongside biological responses. **3**) Life Cycle Assessment (LCA) Models: Tools for evaluating long-term environmental impacts, such as carbon footprint and eutrophication, associated with the construction and operation of offshore wind farms (OWFs).

Scoping review: A structured, stepwise methodology, following an *a priori* protocol to collate and describe existing research evidence (academic and grey literature) on a broad topic area. It follows a systematic map methodology, but with components of the process simplified or omitted to produce information in a shorter period (Please note this is not the same as the 'prescoping' stage of a literature review).

Short Science Summaries (SSS): Concise summaries of scientific evidence generated from the scoping review, intended for broad dissemination and policy support.

Spawning Stock Biomass (SSB): The total weight of mature, reproductive individuals in a fish population or stock capable of spawning (reproducing).

Spillover effect: Spillover effects refer to the movement or transfer of organisms, nutrients, or ecological benefits from one area to adjacent or nearby areas, often as a result of habitat changes or protected zones.

State: Properties and processes of the ecosystem.

Suspended Particulate Matter (SPM): Tiny solid particles that are suspended in the water column, not settled on the seabed. These particles can be either organic (such as plankton and detritus) or inorganic (like silt, clay, and sand).

SPM plume dynamics: The behaviour and movement of Suspended Particulate Matter (SPM) plumes—clouds of suspended sediments and particles—released into the water column, especially during offshore wind farm construction activities.

Threshold value: A value or range of values that allows for an assessment of the quality level achieved for a particular criterion, thereby contributing to the assessment of the extent to which Good Environmental Status is being achieved.

Trophic guild: Group of species that exploit the same type of food resources in a similar way, regardless of their taxonomic relationships. Essentially, it groups organisms based on their feeding habits and ecological roles within the food web.

Trophic cascades: Ecological processes where changes at one trophic level (usually predators) indirectly affect other levels in the food web, impacting the abundance or behaviour of multiple species.

Turbidity: It measures how much light is scattered or absorbed by particles suspended in water. Higher turbidity means less light penetration, which can affect photosynthesis and aquatic life.

Unexploded ordnance (UXO): In the marine environments, unexploded ordnance (UXO) refers to munitions left in seas and coastal waters that did not detonate when originally deployed (from wars, military exercises, or weapons dumping).

Wake effects: The changes in wind flow and turbulence that occur downwind of wind turbines in an offshore wind farm, caused by turbines extracting energy from the wind.

1.

Executive Summary

1 EXECUTIVE SUMMARY

This report is commissioned by the European Commission's Directorate-General for Environment (DG ENV), under the EU-funded ↗ BioAgora project. Its remit was to assess the impacts (including cumulative) of the expansion of offshore wind energy production on the achievement of the good environmental status. The request was submitted by DG ENV to the ticketing system of the EC Knowledge Centre for Biodiversity (KCBD) in December 2023. The request received by the KCBD was handed to BioAgora to coordinate the response. Offshore wind is central to the EU's energy transition, with targets set to increase offshore renewable generation capacity from ~16 GW today to up to 89 GW by 2030 and 366 GW by 2050. However, the expansion of Offshore Wind Farms (OWFs) must align with the EU's environmental legislation, notably the Marine Strategy Framework Directive's (MSFD) requirement to achieve Good Environmental Status (GES) across all EU marine waters by 2030 under 11 ecological descriptors. This report supports and contributes to the EU's efforts in its drive for offshore wind energy expansion. The specific aims of the report are to:

- **Investigate the impacts of fixed-foundation wind turbines** on each of the 11 MSFD descriptors of GES. These include marine biodiversity (D1), non-indigenous species (D2), commercially exploited fish and shellfish (D3), marine food webs (D4), and human-induced eutrophication (D5). They also include seafloor integrity (D6), hydrographical conditions (D7), contaminants (D8), contaminants in fish and other seafood (D9), marine litter (D10), and energy, including underwater noise (D11).

- **Underscore the consequences and cumulative impacts of OWFs** on marine ecosystems.

- **Identify and analyse knowledge gaps** through a scoping literature review and expert participatory workshop.

This report combines the findings of the scoping review and a subsequent participatory workshop with external experts to assess the cumulative impacts of OWFs and knowledge gaps. The scoping review provided a narrative synthesis of the existing evidence related to the above-mentioned aims, with the findings compiled into Short Scientific Summaries (SSS) for each GES descriptor. The participatory workshop gathered expert insights and provided experimental knowledge, including key implications for OWF-associated policies, to support and complement the SSS findings.

Some key takeaways from the Short Scientific Summaries (SSS) for each descriptor are:

1. **Marine biodiversity (D1):** OWFs cause a number of adverse effects on marine biodiversity. Marine mammals, fish, and birds show behavioural displacement in response to underwater sound emissions from wind farm foundation installation. Birds and bats face collision risk. OWFs strongly modify benthic habitats, where foundations in fixed turbines may act as artificial reefs, attracting epifaunal species and other groups, such as cod, thereby altering the functioning of marine ecosystems. For benthic habitats such as flatfish spawning grounds, 2–16% of settlers originate from OWF areas, suggesting that 2–16% of the original spawning habitat overlaps with or is affected by OWFs. However, knowledge gaps remain, particularly around long-term, cumulative, and population-level effects, as well as interactions with climate change and species adaptation.

2. **Non-indigenous species (D2):** Wind turbine foundations are a suitable habitat for several benthic macrofauna species, including the non-indigenous Japanese skeleton shrimp, with species composition and abundance changing over time. However, long-term and site-specific monitoring across diverse habitats is necessary to improve understanding of ecological impacts.

3. **Commercial fish and shellfish (D3):** Through habitat changes, artificial reef creation, and noise disturbance, OWFs influence fish distribution, spawning, and catch rates. These cumulative impacts are likely to alter ecosystems, predator-prey dynamics, and displace fisheries, though large-scale spillover effects remain unproven. Key knowledge gaps identified include long-term impacts of multiple OWFs, interactions with other marine activities, and socio-economic effects on fisheries.

4. **Food webs (D4):** OWFs can alter marine food webs by introducing artificial structures that modify habitat availability, biomass distribution, and nutrient cycling. These installations may reduce fishing activity in some areas, but they also generate disturbances such as noise, sediment resuspension, and habitat modification, which can lead to changes in species composition and trophic interactions. The overall effects on marine food web structure and functioning remain uncertain, as long-term ecosystem responses, spillover dynamics, and interactions with climate change are still poorly understood.

5. **Eutrophication (D5):** By altering nutrient dynamics, phytoplankton growth, and oxygen levels, OWFs can impact eutrophication, with the magnitude of the impacts varying temporally and spatially, and some being region-specific. Key knowledge gaps on long-term and large-scale impacts persist.

6. **Seafloor integrity (D6):** OWFs impact seafloor integrity through physical disturbance, habitat loss, and shifts in carbon cycling dynamics. Moreover, impacts on macrobenthic communities include facilitation of colonisation and increased productivity, including the spread of non-native species and shifts in dominance and species composition. The ecological impact on the seafloor from related management measures, such as bottom-trawling bans within OWFs, remains unclear in the short term. Significant knowledge gaps persist regarding long-term and broader-scale seabed impacts, as well as effects across different stages of OWF development, including decommissioning

7. **Hydrographical conditions (D7):** OWFs significantly alter sediment transport, currents, and wave climate, with monopile foundations causing lasting changes. In addition, impacts were found to be intensified in high-density OWF areas. Key knowledge gaps, particularly the limited availability of long-term studies and regional biases, were identified.

8. **Contaminants (D8):** Although evidence of the impacts of OWFs on contaminants was very limited, some metals released from corrosion protection measures on OWFs were at levels that were not found to cause pollution. Knowledge gaps, including long-term impacts and impacts of emerging contaminants, were identified.

9. **Contaminants in seafood (D9):** no literature was found.

10. **Marine litter (D10):** Evidence of the impacts of OWFs on marine litter is limited. However, the decommissioning phase of OWFs has been identified as a contributor to marine litter, with its spatial distribution dependent on hydrodynamic and geomorphological processes.

11. **Underwater noise (D11):** Impulsive noise generated during installation was found to potentially harm marine mammals, although the main research focus was on a single species, the harbour porpoise. Potential impacts on marine mammals based on measured sound levels included auditory injury. Measured impacts on the harbour porpoises included avoidance of the wind farm area and reduction in acoustic activity. Some behavioural changes in fish were also identified, but evidence was limited and highly variable at the individual level. No effects were demonstrated on marine mammals in relation to continuous noise generated by operational wind turbines, while some fish appear attracted to the turbines. It cannot be established whether that attraction is related to prey availability or a reaction to the sound. Key areas that are understudied were identified, including the impact of electromagnetic fields and noise generated prior to construction and during decommissioning. A significant knowledge gap exists in the assessment of acoustic effects on marine mammal species other than the harbour porpoise. Furthermore, the population-level effects and potential impacts of multiple wind farm installations remain poorly understood to date.

While the participatory workshop allowed for rich discussions across four clusters, common themes emerged relating to the complex and nonlinear ways in which the changes induced by OWFs propagate through the wider marine ecosystem, with the need for integrated, long-term and cross-disciplinary approaches to assess and manage the cumulative impacts of OWFs. Among the many points discussed by participants were the lack of standardised methodologies to evaluate the cumulative effects—particularly across time scales—and limited research on the decommissioning phase of OWFs, which likely contributes to significant yet poorly understood impacts. Additionally, the focus of current research on small-scale, short-term studies, which fail to capture transboundary and ecosystem-level changes, was raised. Furthermore, the mandatory disclosure of turbine materials and long-term contaminant monitoring, including microplastic tracking, particularly in multi-use regions where OWFs overlap with fisheries, was highlighted as essential for managing health risks associated with pollution. The need to understand how the presence of OWFs may accelerate or promote the spread of certain species was discussed. At present, the MSFD does not address issues of connectivity and species dispersion, including the spread of invasive alien species, particularly in relation to shipping activities.

In conclusion, this report highlights the necessity for a comprehensive, long-term, and integrated approach for evaluating and managing the effects of offshore wind energy production at sea, including cumulative impacts on marine ecosystems. Significant gaps in knowledge persist, and addressing them through improved monitoring, cross-disciplinary research, the development of new and standardised assessment methodologies, and adaptive policy frameworks will be essential to ensure that Good Environmental Status is achieved.

2. Introduction

2 INTRODUCTION

2.1 Background

This report was prepared by ↗ Eklipse in response to a request from the European Commission's Directorate-General for Environment (DG ENV) submitted to the Science Service for Biodiversity (SSBD, BioAgora) via the EC Knowledge Centre for Biodiversity (KCBD) ticketing system. The report contributes to addressing the policy needs regarding the assessment of the cumulative impacts of offshore wind farms on marine ecosystems across the EU. This request is funded by the EU Horizon Europe project "Connecting biodiversity knowledge and decision-making", mandated to build the future EU Science Service for Biodiversity (SSBD). – ↗ BioAgora.

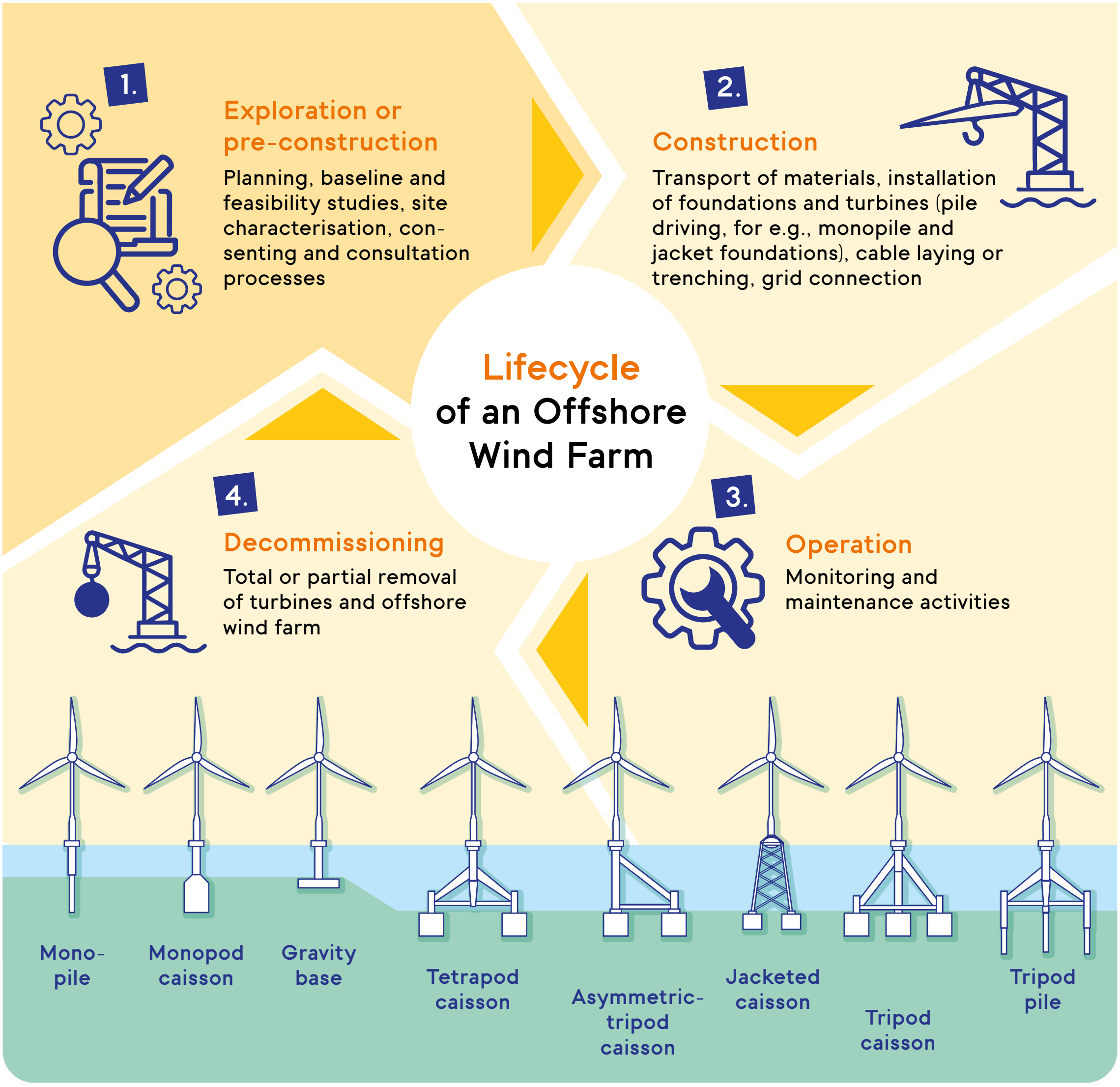

Figure 1 Lifecycle stages of an offshore wind farm and different types of fixed-bottom foundations (based on Bhattacharya, S., 2014).

The report examines the multi-level impacts of offshore wind farms. Such analysis is critically needed, given that they represent a main pillar of the targets set by the European Union (EU) for renewable energy sources to achieve a production capacity of 86-89 GW by 2030 and 355-366 ↗ GW by 2050. The EU's total offshore installed capacity currently stands at around 16.3 GW, with the ambition to increase new offshore installations to almost 12 GW per year on ↗ average. While both fixed-bottom and floating foundation wind farm projects are planned or already in place, this study focuses solely on the evidence and potential impacts of the former type of foundation (→ Figure 1).

This report aims to undertake an analysis relevant to all descriptors of GES under the Marine Strategy Framework Directive (MSFD) and to identify knowledge gaps with a particular focus on cumulative impacts. The analysis includes a literature review (hereafter referred to as a scoping review) and an expert consultation assessing how offshore wind energy expansion could affect the achievement of GES, while considering the threshold values set by EU Member States for several GES descriptors (such as seabed integrity, underwater noise, contaminant levels, species abundance, etc.) and the subsequent cumulative impacts.

Environmental impacts can stem from a range of activities within a given area or region, where individual effects may not be significant if assessed in isolation. Building up from these individual impacts, cumulative impacts are defined as:

> *The impacts (positive or negative, direct and indirect, long-term and short-term impacts) arising from a range of activities throughout an area or region, where each individual effect may not be significant if taken in isolation. Such impacts can arise from the growing volume of traffic, the combined effect of a number of agricultural measures leading to more intensive production and use of chemicals, etc. Cumulative impacts include a time dimension since they should calculate the impact on environmental resources resulting from changes brought about by past, present and reasonably foreseeable future actions' (European Commission, 1999).*

This report provides science-based insights for the EU Commission in the context of the Member States' MSFD Programmes of Measures and the upcoming MSFD review planned by the Commission to ensure that offshore wind energy expansion does not hinder the achievement of GES under the MSFD. To support this, we considered the entire lifecycle of offshore wind power plants, including decommissioning (→ Figure 1).

2.2 Objectives

The main goal of the request from the Directorate General for Environment (DG ENV) is to enhance understanding of the potential impacts of OWF expansion on achieving GES, as defined by the MSFD.

Specifically, the report aims to:

- **a. Investigate** the impacts of fixed-foundation wind turbines and grid connection infrastructure expansion on each of the 11 descriptors of GES under the MSFD (→ Figure 2), as described in ↗ www.environment.ec.europa.eu/, throughout the life-cycle[1] of a wind farm.
- **b. Assess** the consequences of the cumulative impacts on marine ecosystems.
- **c. Identify and analyse** knowledge gaps through literature review, expert consultation, and a participatory workshop.

1 The life-cycle of a wind farm considers initial surveys (planning phase), construction, operation and decommissioning.

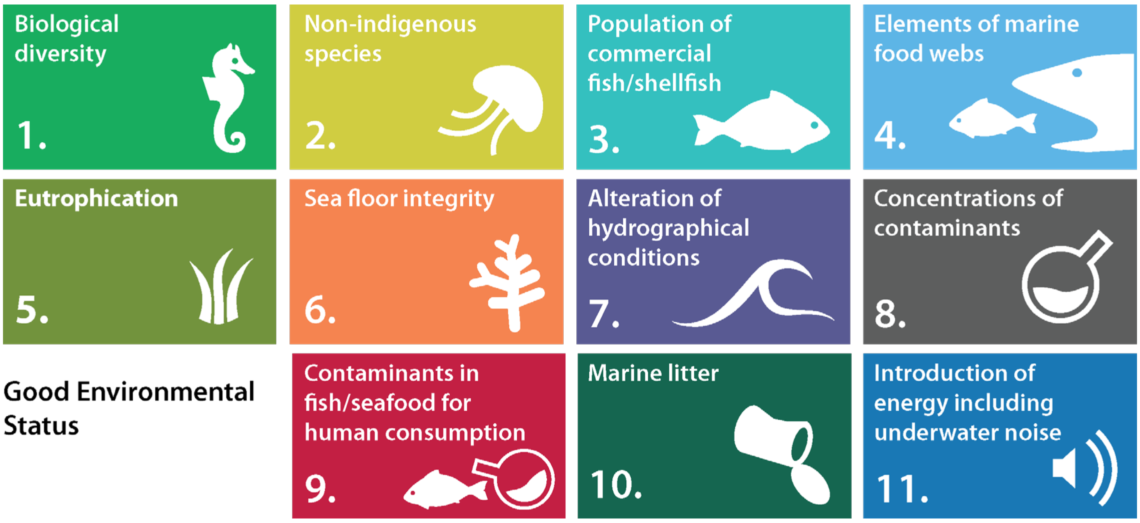

Figure 2. Illustration of the 11 qualitative descriptors for determining good environmental status as presented in Directive 2008/56/EC of the European Parliament and the Council (see ↗ ©OSPAR)

2.2.1 Policy relevance and geographical scope of the request

The request primarily aims to contribute to the MSFD (and its ongoing review). It will inform other EU legal instruments/policies such as the Maritime Spatial Planning Directive, Birds and Habitats Directives, Renewable Energy Directive, Biodiversity Strategy, Zero Pollution Action Plan, Marine Action Plan, Wind Power Action Plan, Nature Restoration Regulation and the Oceans Pact, as well as regional and/or international agreements or processes, notably the Regional Seas Conventions and Action Plans/activities, and other possible initiatives planned/taking place at a regional level through:

- **a. The negotiation or implementation of a legal act** (Directive, Regulation, Decision),
- **b. The negotiation or implementation of a non-binding instrument** (e.g., Strategies, Communications),
- **c. The drafting of EU action plans or legislative proposals** (either at the development, negotiation, or adoption phase).

The geographical scope of the request is focused on the European Union marine regions and subregions as defined under the MSFD: the Baltic Sea, the Black Sea, the northeast Atlantic (including the North Sea, the Celtic Seas, the Bay of Biscay and the Iberian Coast, and Macaronesia), and the Mediterranean Sea (including the western Mediterranean Sea, the Adriatic Sea, the Ionian Sea, the central Mediterranean Sea, and the Aegean-Levantine Sea).

2.2.2. Relevance for biodiversity

Due to the targets set in the EU and national legislation and policies, the planned developments of offshore wind production are likely to occur on such a large scale that they will have an impact on the structure of marine ecosystems and, consequently, their functioning. Impacts from offshore wind developments may include loss of seabed habitat, disruption of migratory routes, physical injury or mortality, disturbance of feeding and breeding grounds, introduction of underwater noise and electromagnetic fields, inputs of litter and contaminants, as well as changes in hydrographic conditions. Almost all descriptors of GES may be impacted by/interact with these developments.

2.2.3 Cumulative impacts

Several interpretations are possible for defining cumulative impacts. The following were considered and used:

- **Cumulative effects of wind farms**. In this context, the impact would aim to assess the additional effects of introducing a wind farm into an environment where other anthropogenic activities are already taking place or are planned (e.g., oil and gas exploration, shipping).
- **Impacts arising from the development** of more than one wind farm that may overlap temporally or spatially, leading to cumulative effects on a population or habitat.
- **Cascading effects**, attributed to the cumulative impacts that escalate within the ecosystem.

2.2.4 The MSFD structure in relation to the request

The MSFD is divided into 11 descriptors encompassing ecosystem state features[2] and pressures[3]. It is therefore challenging to discuss potential relationships between OWF and individual descriptors in isolation. This is because the descriptors are often linked to each other, as previously highlighted by Berg et al. (2015) (→ Table 1).

Table 1. Qualitative descriptors for determining good environmental status in the MSFD (EU, 2008). The column on the right classifies the descriptors according to the presence of corresponding pressure or state criteria/attributes within the descriptor (following the Driver-Pressure-State-Impact-Response DPSIR framework) (Berg et al., 2015).

MSFD DESCRIPTOR	SHORT NAME	CLASSIFICATION
Marine Biodiversity	D1	State
Non-indigenous species	D2	Pressure/state
Commercially exploited fish and shellfish	D3	Pressure/state
Marine food webs	D4	State
Human-induced eutrophication	D5	Pressure/state
Seabed integrity	D6	Pressure/state
Hydrographical conditions	D7	Pressure/state
Concentrations of contaminants	D8	Pressure
Contaminants in fish and other seafood	D9	Pressure
Marine litter	D10	Pressure
Energy, including underwater noise	D11	Pressure

The knowledge synthesis aimed to highlight the connections between OWFs and the individual MSFD descriptors. However, because descriptors are sometimes linked via pressure-state relationships, readers will need to seek information relevant to an ecological compartment or taxonomic group, along with its ecological status and relevant pressures. For instance, D1 on benthic habitats (state descriptor) is inherently linked to D6 on seabed integrity (pressure descriptor, → Table 1). OWFs are known to introduce artificial structures on the seabed, resulting in a physical loss and/or disturbance of benthic habitats during the construction phase. This means OWFs are another pressure that can be described in the frame of D6, while also affecting the state of benthic habitats in D1. In this case, someone interested in benthic habitats and seabed disturbance/loss would need to examine the effects of OWF on both D1 and D6. Similar reasoning can be applied to all interlinked descriptors.

2 States are properties and processes of the ecosystem.
3 Pressure is defined according to Robinson et al. 2008 as "the mechanism through which an activity has an effect on any part of an ecosystem".

3. Methodological framework

3. METHODOLOGICAL FRAMEWORK

To address the request and achieve the objectives stated above, the following two-stage methodological process was undertaken:

- **Stage 1)** A scoping review (SR) producing Short Science Summaries (SSS) that was used to inform a broader participatory process in stage 2.
- **Stage 2)** A virtual participatory workshop to discuss the SSS outputs whilst focusing on knowledge gaps, and resultant policy and research implications.

To ensure a structured synthesis of the scientific literature and elicit knowledge, a SR provided a rapid standardised view of recent peer-reviewed evidence, while the Expert Consultation workshop covered views, opinions, and experience-based knowledge on the key issues related to the review question, in accordance with the PerSPEcTiF framework (Booth et al., 2019), see → Table 2 below. Note that this scoping review followed the detailed methodology described in the *a priori* Methods Protocol (see ↗ www.eklipse.eu/request-offshore-wind-farms), which was peer-reviewed before Stage 1 commenced. The participatory workshops adhere to a robust ethical infrastructure comprising twelve measures to mitigate potential ethical risks (cf. → Annexe 1 for full details).

Table 2. Key components of the review question according to the PerSPEcTiF framework (Booth et al., 2019). Note that all search strings related to the question framework are listed in → Annexe 3.

PERSPECTIVE	SETTING	PHENOMENON OF INTEREST	ENVIRONMENT	TIMING	FINDINGS
Academic literature, scholarly reviews	European regional seas	Impacts of offshore wind farms on the achievement of Good Environmental Status (GES)	Marine environment	2008 - present	Permanent and short-lived impacts of offshore wind farms on marine ecosystems linked to the 11 descriptors of GES, i.e., marine biodiversity (including bats*), non-indigenous species, commercial fish and shellfish, food web, eutrophication, seabed integrity, hydrological conditions, contaminants, contaminants in seafood, marine litter and underwater noise; cumulative nature of impacts.

**Note that bats are included in the findings of our report; this inclusion was considered an important addition to the scoping review, given the increasing primary evidence describing the impacts of OWFs on this species group.*

3.1. Stage 1: Scoping review for SSS

The scoping review (SR) provides an overview of the distribution and extent of existing evidence relating to the above-mentioned objectives. It helps identify and assess knowledge gaps, for which further information was sought through expert consultation and a participatory workshop. The SR was conducted in close accordance with the guidelines and standards for quick scoping reviews (Collins et al., 2015; Dicks et al., 2017). Thus, the SR follows a structured methodology – following an *a priori* protocol – to collate and synthesise the existing research evidence into SSS per GES descriptor. A systematic review was not feasible within the proposed timeframe. Whilst less time intensive than a systematic review, the SR can be applied to understand the impact of either a 'pressure' on a system or a policy-driven intervention. It is designed to be transparent and to minimise bias (Collins et al., 2015).

3.1.1 Search strategy

A search for peer-reviewed scientific literature was conducted using the Web of Science Core Collection (WOSCC) and Scopus. Note that grey literature was excluded from the search because of the proposed time frame, and to focus solely on the most objective scientific (i.e., peer-reviewed) knowledge of effects and impacts. The searches were conducted in the indexed articles' titles, abstracts, and keywords (i.e., using the "Topic" field tag in WOSCC, and "TITLE-ABS-KEY" tag in Scopus). The search strings are shown in → Table A3.1, Annexe 3, and were based on the criteria for the descriptors as stated in Article 8 of the European Commission Decision on ↗ GES 2017/848 document. Boolean operators (e.g., AND) were used to connect keywords in search queries related to OWFs to have focused and productive results. After the search was completed, all references were exported and archived into a bespoke Excel database. Duplicates were also identified and archived before screening.

3.1.2 Eligibility criteria

Once the searches were completed, studies were filtered using a predefined set of inclusion and exclusion criteria. Indeed, the eligibility of each article was based on a list of criteria corresponding to the PerSPEcTiF framework (cf. → Annexe 4, Table A4.1 for the full list of criteria).

3.1.3 Screening strategy

Following the predefined eligibility criteria stated above, the study selection process consisted of a two-phase screening. In the first phase, all titles and abstracts were screened. In the second phase, a full-text screening was undertaken. Thus, if the qualifying information was not detailed sufficiently to reject or to retain a title/abstract with certainty in the first phase, then the publication in question was retained for assessment in the next eligibility step (i.e., full-text screening) (→ Figure 3).

3.1.4 Data extraction and synthesis

The following data, extracted from the retained scientific literature, were entered into bespoke online Google Sheets, which were used to produce the SSS. All data were extracted in a repeatable, objective, and structured manner following the PerSPEcTiF framework (cf. → Annexe 4 for the full list of variables extracted).

Perspective characteristics:

- Publication details (i.e., authors, publication year, and type)
- Time frame: data collection period, i.e., when data were collected (different from the publication year)

Setting characteristics:

- Geographical location, according to the MSFD regional and sub-regional seas (e.g. Baltic Sea, Black Sea, Mediterranean Sea and northeast Atlantic - North Sea, Bay of Biscay, Celtic Sea, Iberian Coast).

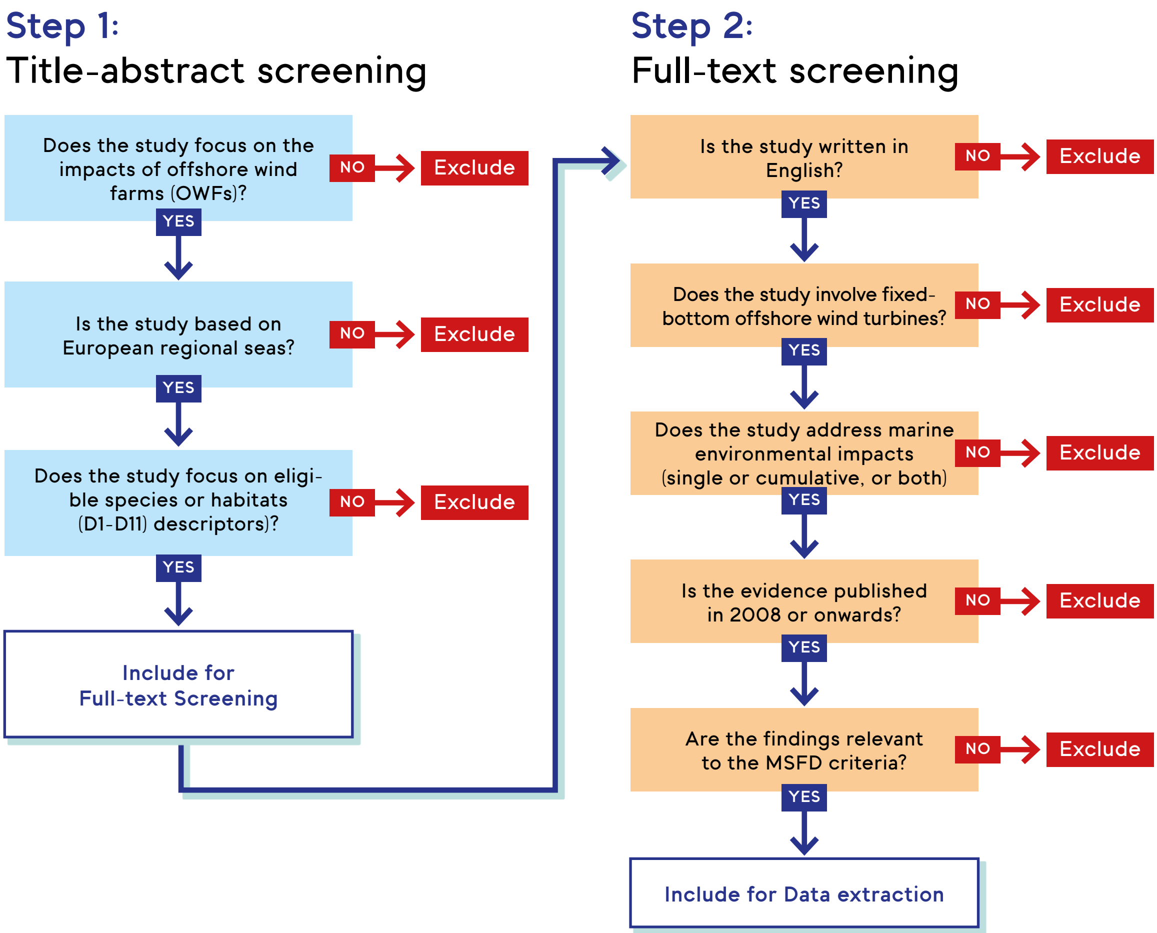

Figure 3. Decision trees illustrating the two-stage screening process: title and abstract screening (step 1 on the left) and full-text screening (step 2 on the right). These decision trees illustrate the primary criteria used to select relevant literature. Full details can be found in → Table A4.1 in Annexe 4, which outlines the selection criteria.

Phenomenon of interest characteristics:

- Subject of interest: i.e., species groups, or habitats impacted.
- Exposure characteristics:
  - Type of wind farm turbines causing impacts (following the typology from Rezaei et al. 2023):
- Fixed-bottom offshore wind turbines:
  - (i) Monopile;
  - (ii) Tripod;
  - (iii) Jacket;
  - (iv) Suction caisson;
  - (v) Gravity base;
  - (vi) Tripile;
  - (vii) Twisted jacket.

Findings' characteristics:

- Characterisation of the pressures-impacts relationship for each GES descriptor.
  - Relative to three different lifecycle stages: 1) installation, 2) operation, and 3) decommissioning.
- Evidence of impact measured or observed for each descriptor (i.e., relating to individual GES descriptors):
  - Impact metric used to measure the effect of OWFs.
  - associated MSFD criteria for GES, where relevant

Additional characteristics:

- Study design: Control-Impact (CI) (reference site or site comparison), Before-After (BA) (temporal comparison), After only (multiple points in time), Before-After-Control-Impact (BACI), gradient sampling design, or No comparator.
- Lastly, where any of the above information was not specified in the retained literature, it was coded as "Unspecified".

Experts were divided into specific groups working collaboratively to screen and develop the analysis, with one member of the Eklipse Methods Expert Group (MEG) closely monitoring the overall process. The Expert Working Group (EWG) and the MEG collaborated to address any uncertainties during data extraction and made joint decisions in accordance with best practice principles.

3.1.5 Mapping and data presentation

A scoping database was compiled, including all relevant metadata from the retained documentation after the full-text screening stage. For cases where more than one type of impact (i.e., Finding) was reported (measured or observed) in the same document, a unique entry in the Excel database was made. This necessitated the use of specific data entry IDs (e.g., name_et_al_2008_1, name_et_al_2008_2). Thus, we allowed multiple entries per article when different species groups or subjects (cf. "Subject of interest" above) relevant to MSFD descriptors were assessed (e.g., Marine mammals, Fish, Cephalopods, etc.) if studies provided data for specific functional or ecological subgroups (e.g., "richness of demersal fish," at the whole-community level, and at the species level (e.g., "abundance of species"), both were extracted.

Regarding species group classifications, we followed the MSFD groupings defined in ↗ Commission Decision (EU) 2017/848 to ensure compatibility with national reporting frameworks and descriptor-level assessments.

Concerning the findings, we grouped impact metrics into higher categorical groups following recognised methods. For instance; 1. "Mortality/Risk": metrics including mortality rates and survival probabilities; 2. "Space Use": metrics including movement, flight patterns, home ranges, and site fidelity; 3. "Species population": metrics including abundance, density, structure, composition, biomass; 4. "Reproduction potential": metrics related to spawning, larval settlement, and reproductive potential; 5. "Feeding/trophic": metrics including diet composition, stomach content; 6. "Behaviour" metrics including behavioural responses, e.g., communication (e.g., vocal), social structure, stress/vigilance levels, respiration.

Findings are presented in SSS for each descriptor. The SSS aims to describe findings on impacts, including those presented cumulatively. Knowledge gaps (under-represented subtopics) and knowledge clusters (well-represented subtopics) were identified by cross-tabulating metadata (e.g., study subject, exposure characteristics, findings' characteristics, etc.).

3.2 Stage 2: Participatory workshop using external experts

A three-hour virtual participatory workshop was held on April 10, 2025 to explore and assess the findings of the scoping review. The primary aim of the workshop was to capture expert knowledge and insights, to validate and expand upon the scoping review's findings, particularly in identifying knowledge gaps and generating additional evidence focused on managing cumulative impacts. The workshop also aimed to identify possible mitigation actions or recommendations for each of the 11 descriptors related to the core phenomena of interest, including cumulative impacts, physical and chemical processes, effects on habitats and biodiversity, and broader ecological interactions, as well as potential mitigation strategies.

The Mural[4] Platform was used to collect information both through a pre-workshop task and during the interactive workshop and break-out sessions, all facilitated by experienced moderators. Participants were divided into four breakout groups, each focusing on a specific set of descriptors. Each group session was supported by a facilitator, and administrative assistance was provided by Eklipse members (MEG, KBD and EMB). The workshop concluded with a plenary session, bringing all participants together to synthesise findings and identify shared themes, key challenges, and opportunities.

3.2.1 Recruitment

Workshop participants were identified based on their thematic expertise, as well as their alignment with specific gap areas or descriptors used in the analysis, and their professional experience. Participants were drawn from a range of sectors, including academia, consultancy, NGOs, industry, and policymaking, using the Eklipse network and established Eklipse methods for expert consultation. Additionally, members of the EWG who were identified actively contributed by recommending external experts identified through the reviewed literature. Further participants were identified through consultation with organisations involved in related but independently conducted reports, such as the International Council for the Exploration of the Sea (ICES), the European Environment Agency (EEA), and IFREMER.

The initial aim was to recruit 30–40 participants, with an even distribution across the thematic clusters. Ultimately, 29 participants were secured, with representation from all clusters (see → Table 3 and → Annexe 5).

3.2.2 Workshop format and outcomes

To optimise both the outputs and the participant experience, a briefing paper was circulated in advance alongside the SSS. The workshop was conducted as a virtual webinar via Zoom, featuring contributions from the EWG, the requester, and workshop participants (→ Annexe 6).

As the number of descriptors exceeded five and the associated gap areas varied, sub-categories were either merged or key gap areas prioritised in clusters (→ Table 3). This was adopted as a pragmatic and efficient strategy to address the scope of the request.

Table 3. Cluster of descriptors defined for the workshop.

CLUSTER NUMBER	NAME OF THE CLUSTER	DESCRIPTORS
1	Noise, birds and mammals	D1 mammals, birds, D11
2	Habitats and seabed integrity	D1 benthic habitats, D2, D5, D6
3	Contaminants and litter	D8, D9, D10
4	Fish, fisheries, and food webs	D1 fish & cephalopods, D3, D4, D7

4 Mural is a collaborative participatory work platform https://www.mural.co/

The workshop was structured around the following six phases:

1 A summary presentation of the report and SSSs.
2 A detailed discussion of the knowledge gaps within each cluster, using the pre-workshop outputs (indicatively → Figure 4 and → Figure 5) as a starting positions.
3 Suggestions for actions and research to address the identified knowledge gaps.
4 Additional comments related to the descriptors and overarching goals of the request.
5 Presentations of findings from each cluster.
6 A plenary discussion to synthesise findings across clusters, with a focus on identifying opportunities for future action.

An illustrative extract is provided below to highlight the nature of these discussions (→ Figure 4 and → Figure 5).

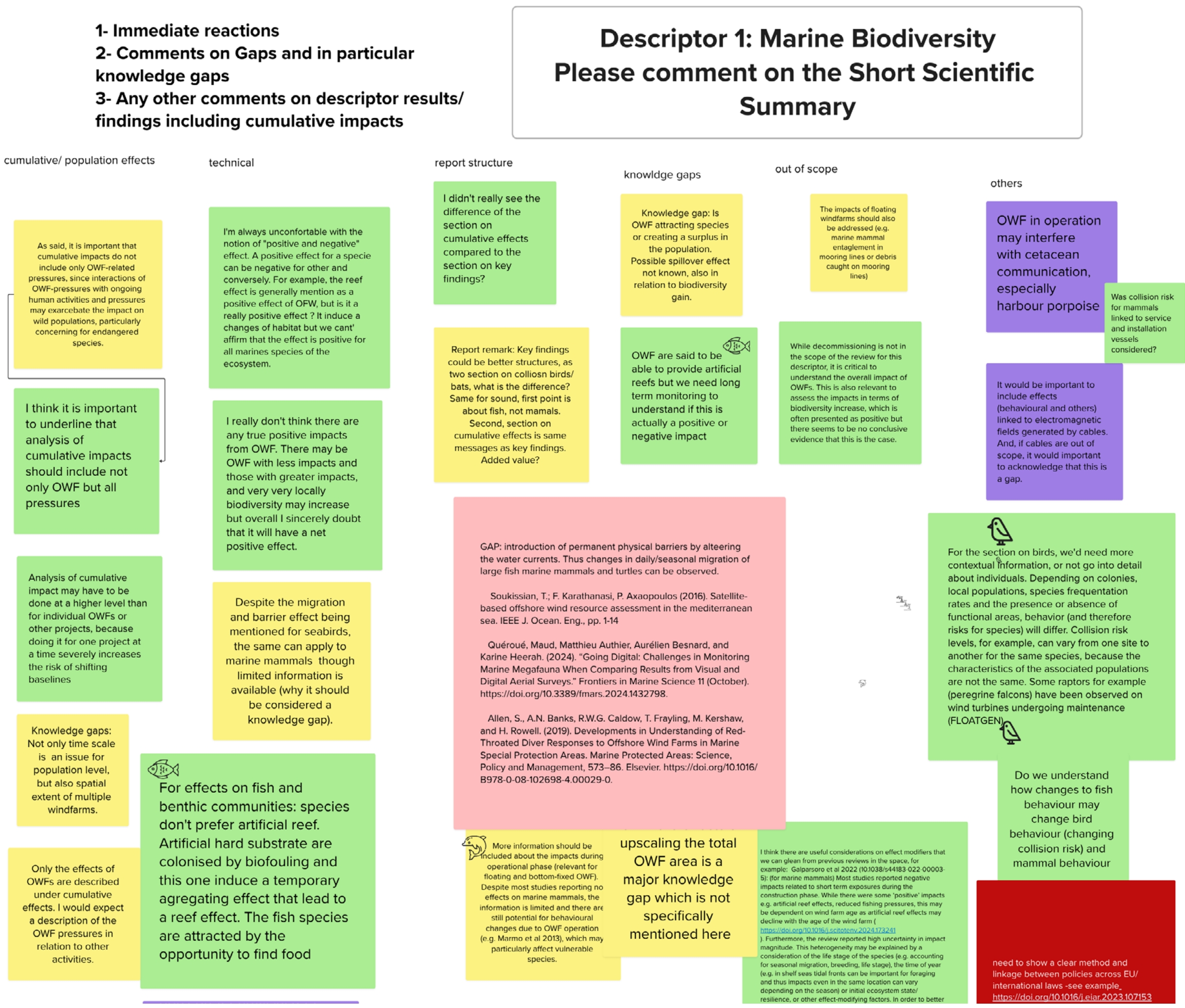

Figure 4. Example of a pre-workshop exercise (screenshot Descriptor 1), which required Experts to comment on the short science summaries prior to discussions commencing in the online workshops.

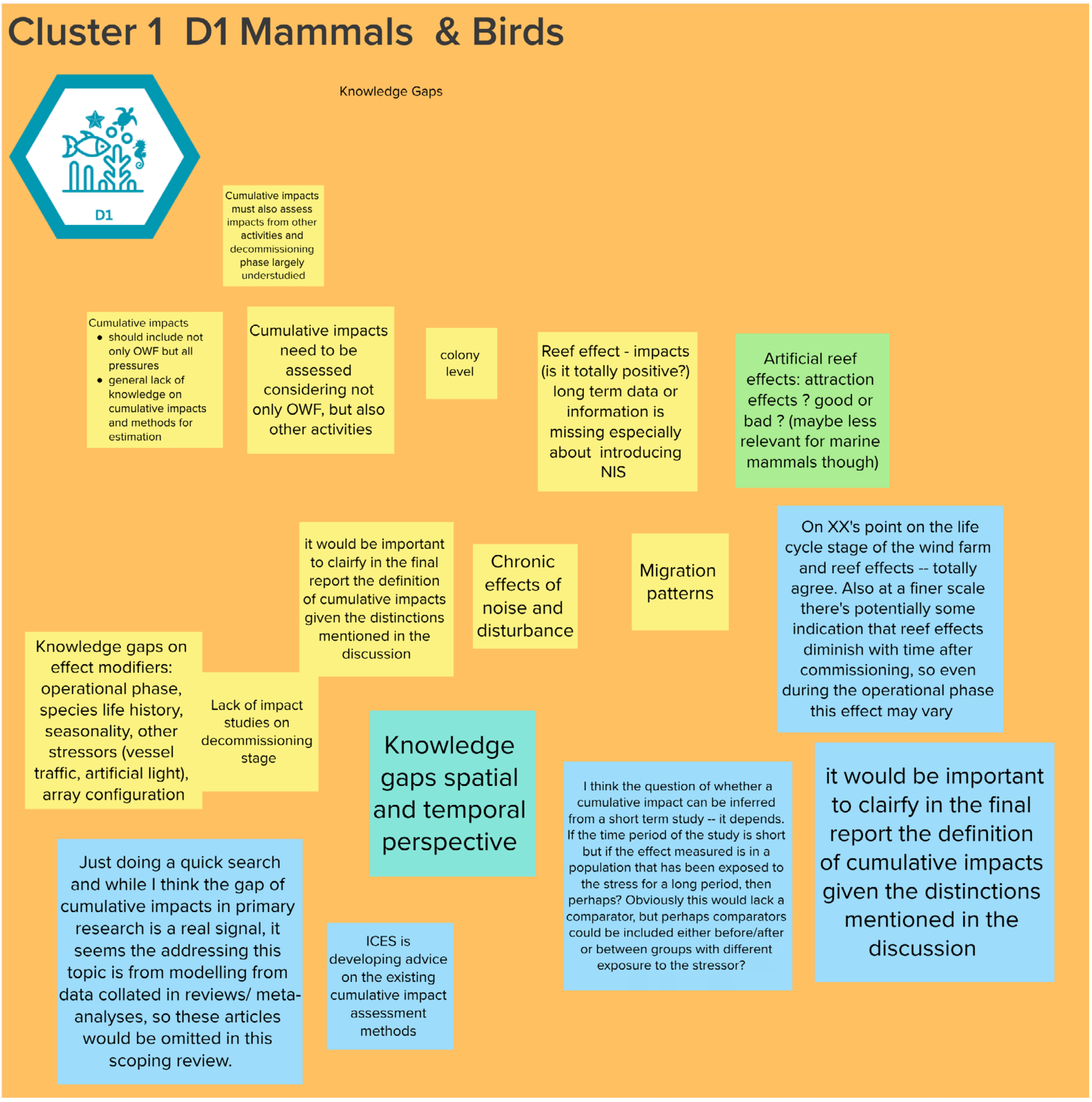

Figure 5: Example showing the accumulation of knowledge gap topics mentioned and listed by Experts during the discussions in the breakout group (cluster 1).

To minimise potential bias, participants were not remunerated for their time, thereby avoiding financial motivations for participation. However, they were given the option to be named in the final report as contributors. Ethics approval for the workshop was obtained from the Ashoka Trust for Research in Ecology and the Environment (reference: IRB/OTH/001/SBh/04/2025; Annexe 2). In line with best practice, written consent was secured for participation, recording, data storage, and the declaration of any conflicts of interest.

The data generated from the workshop are currently stored on a password-protected Google Drive with access restricted to EWG and MEG members. In the longer term, all data will be collated and managed in accordance with Eklipse's data collection and storage protocols, retained for five years, and then permanently deleted.

4. Results

4 RESULTS

4.1 Short Scientific Summaries

Each SSS presents a narrative synthesis of findings from the SR for a specific MSFD descriptor. When a descriptor is a state descriptor (→ Table 1), findings are framed in terms of how OWF might impact the ecological status of the descriptor and its component criteria. When the descriptor is a pressure descriptor, findings are framed around how OWF may interact with the pressure descriptor and its component criteria. Summaries are structured according to the following subsections to give the best insights into the status of knowledge on OWF effects on MSFD descriptors: (i) context related to the descriptor and its criteria according to the MSFD (ii) impacts of offshore wind energy on the descriptor, including information on the selection process (iii) cumulative effects (iv) identified knowledge gaps (v) conclusion.

4.1.1 Descriptor 1. Marine biodiversity

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Context

Under the MSFD, descriptor 1 encompasses all marine species, including seabirds, marine mammals, reptiles, fish, and cephalopods, found in EU waters. Additionally, descriptor 1 encompasses both pelagic and benthic habitats. To be considered in Good Environmental Status (GES), the species' long-term viability must be ensured, the quality and occurrence of habitats must be sufficient, and the distribution and abundance of species need to be in line with prevailing physiographic, geographic and climatic conditions. To ensure a GES, a number of GES criteria need to be met:

- **D1C1:** species' mortality rates are below levels which threaten the species.
- **D1C2:** the population abundance of the species is not adversely affected by anthropogenic pressures.
- **D1C3:** population demographic characteristics (e.g., body size or age class structure, etc) of the species are indicative of a healthy population.
- **D1C4:** species distributional range and patterns are in line with prevailing physiographic, geographic and climatic conditions.
- **D1C5:** regarding benthic habitats, the habitat for species has the necessary extent and condition to support different life history stages.
- **D1C6:** regarding pelagic habitats (i.e., the water column) - the condition of the habitat, including its biotic and abiotic structure and its functions (e.g., its typical species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), is not adversely affected by anthropogenic pressures.

Indeed, OWFs can impact marine biodiversity both positively and negatively, with outcomes influenced by factors such as location, scale, design, and management practices. We present key findings from the evidence base below.

Impacts of offshore wind energy expansion on marine biodiversity

Literature searches and screening process

The ROSES flow diagram below (→ Figure 6) illustrates the screening process. Our literature search for descriptor D1 yielded 339 records identified from WOSCC and Scopus. After removing duplicates, 236 records were screened. At title and abstract screening, 112 records were excluded. 122 full-texts were retrieved for screening, of which 34 were excluded. 24 additional records considered relevant for D1 retrieved from other literature searches (i.e., a unique literature search was conducted per descriptor) were included (see → Annexe 3) . A total of 102 relevant documents (excluding Reviews) were included in the SSS.

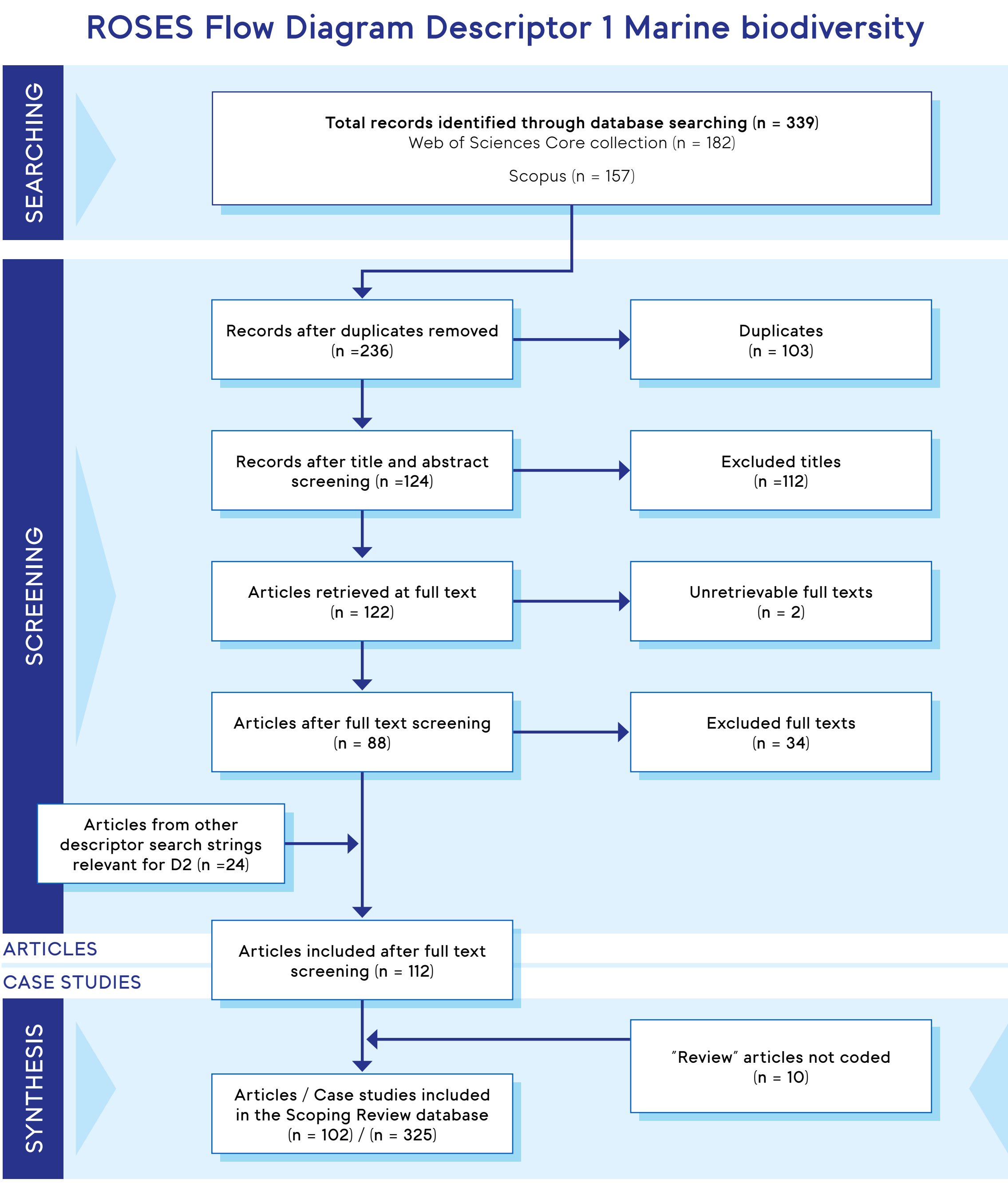


Figure 6. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D1.

Publication trends and data collection duration

Our scoping review focused solely on the period since the MSFD was ratified, from 2008 to the present. Few articles were published concerning D1 before 2012 (→ Figure 7). There was an increase from 2015 onwards, with 14 articles published in 2023. Regarding the study type, the corpus consists of 96% peer-reviewed journal articles and 4% books and conference papers. 71% of articles were empirical studies, 21% modelling, and 9% Reviews (Please note that reviews are not coded hereafter). Concerning data collection periods, the majority of case studies were either very short term (i.e., <1 year) or short term (i.e., 1-4 years).

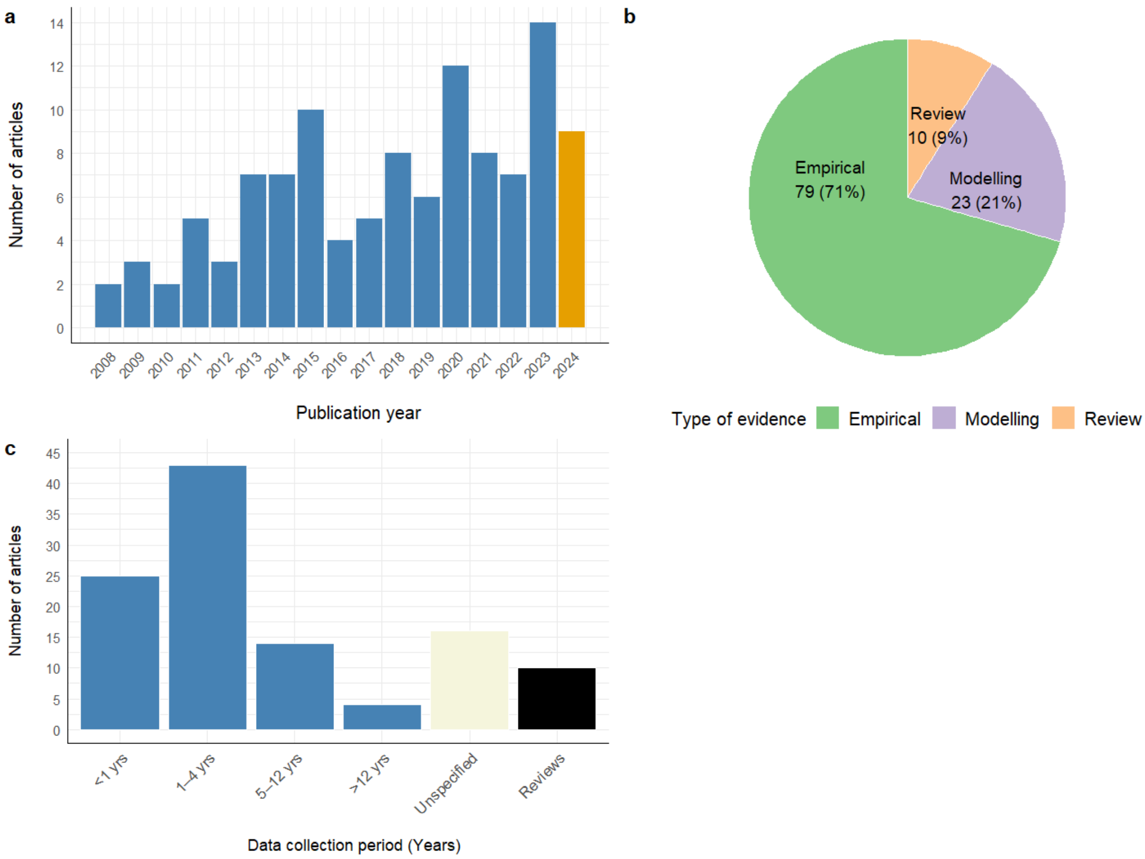
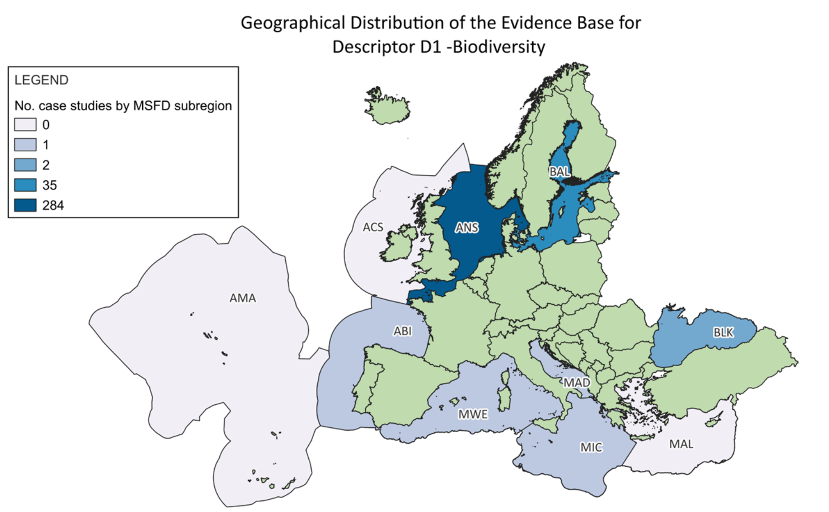


Figure 7: Distribution of retained articles for descriptor 1. Panel (a) shows the number of documents published per publication year (please note that 2024 (orange bar) is not a complete year: literature searches were run in October). Panel (b) illustrates the distribution of the type of evidence. Lastly, panel (c) illustrates the number of articles per data collection period. Please note that in panel (c), "Reviews" (black bar) corresponds to Review type evidence (i.e., where data collection periods were not applicable); "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection periods.

Geographical distribution of the evidence base

Regarding descriptor 1, a clear trend is evident: most case studies (n = 284) are conducted in the North Sea (→ Figure 8). Indeed, these 284 individual impact studies were undertaken either in the English Channel, Kattegat, or the UK Exclusive Economic Zone (EEZ).



Additional Information: No. articles by MSFD subregion										
MSFD subregion	ACS	AMA	MWE	ABI	BLK	MAD	MAL	MIC	BAL	ANS
No. articles	0	0	0	1	1	1	1	1	15	85

Figure 8*. Number of case studies and number of articles by MSFD subregion for descriptor 1. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD).*

OWF characteristics

Nearly 95% of the studies focus on monopile turbines and gravity foundation structures. Most of the current OWF research focuses on construction and operational stages, while critical knowledge gaps persist in pre-installation planning and the decommissioning phase.

Methodological approaches and trends in study designs

Impacts and cumulative impacts are measured using a range of study designs. The majority of studies only have very short (<1 year) or short (1-4 years) data collection periods; few studies applied data collection periods greater than 12 years (→ Figure 9, panel a). Many short-term studies did not use comparators (i.e., compared to the absence of wind farms). Control-Intervention (CI) designs were used across most study durations (→ Figure 9). Longer-term studies predominantly used Before-After (BA), Before-After Control-Impact (BACI), BACI + time series, or CI + time series designs. This corresponds to the observation that most studies focus on short-term impacts with limited understanding of how OWFs affect populations over generations and across spatial scales.

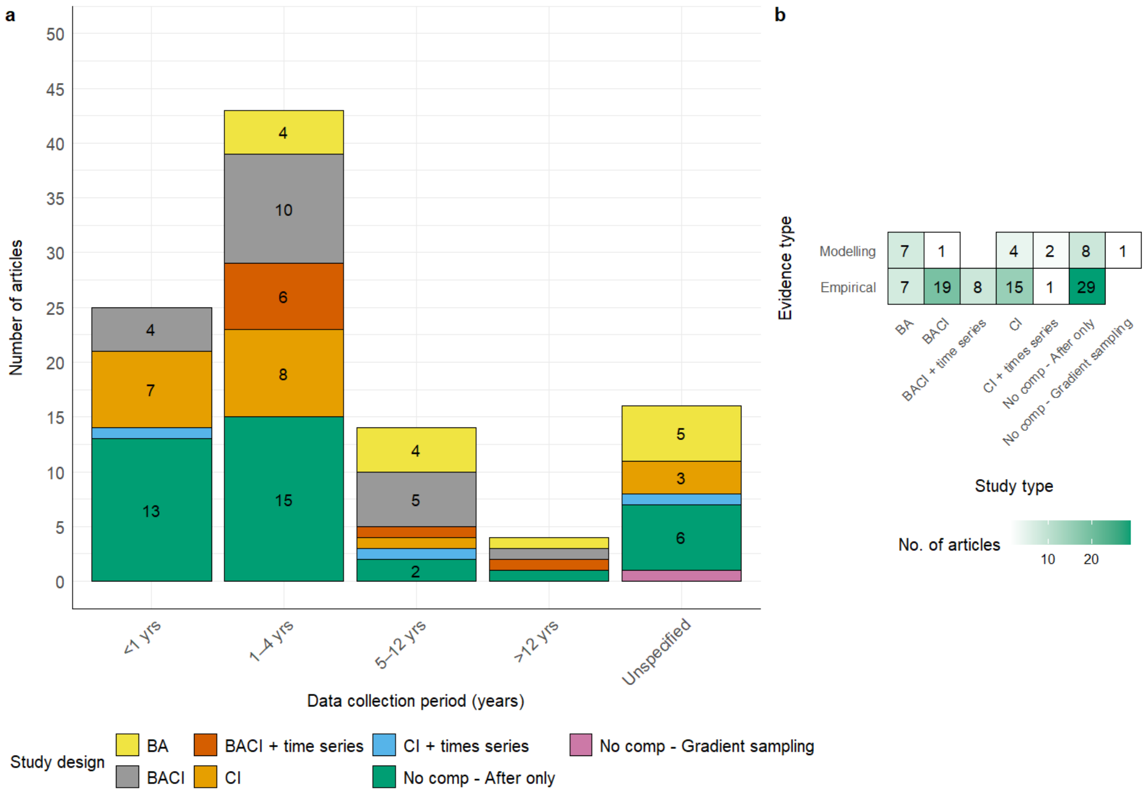


Figure 9: Distribution of evidence type, study design, and data collection periods for descriptor 1. Panel (a) illustrates the number of articles by data collection period and study. Design NB in Panel (a), the number of articles >1 is shown on bar plots. Panel (b) illustrates the total number of articles by evidence type and study design.

Ecological compartments and evidence themes

Case studies focused on mammals, birds, habitats (benthic or pelagic), fish, and bats (→ Figure 10). Two case studies were found on cephalopods (employing modelling methods). Most findings focused on species populations (e.g., abundance, density characteristics, and biomass metrics) across both empirical and modelling evidence, covering all D1 marine biodiversity compartments. Other well-represented themes included the use of space by seabirds (based primarily on empirical evidence), habitat quality for benthic habitats (primarily modelled evidence), mortality risks for birds, and reproductive potential for fish (→ Figure 10 and → Figure 11). However, evidence on space use and feeding for marine mammals was limited. Overall, behaviour metrics were the least covered themes in relation, while species populations were most studied across all groups.

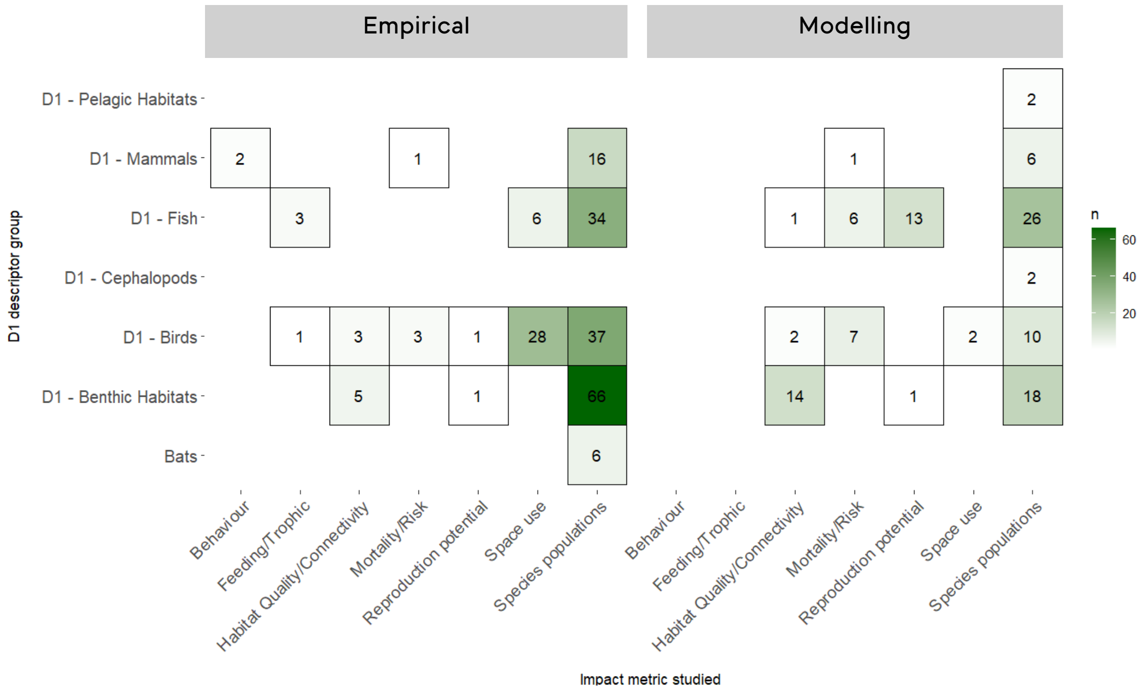


Figure 10: *Heatmap illustrating the distribution of the type of evidence across different descriptor 1 subcategories and impact metrics. The colour intensity represents the quantity of evidence, with darker shades indicating higher levels of evidence. The y-axis corresponds to MSFD subcategories for descriptor 1, and the x-axis corresponds to our impact metrics groupings. Please note that impact metrics categorical groups from left to right: "Behaviour": metrics including, for example, behavioural responses such as vocal communication, stress/vigilance levels, respiration; "Feeding/trophic": metrics including, for example, diet composition, stomach content; "Habitat Quality/Connectivity": metrics including, for example, habitat quality, grain size distribution, habitat disturbance; "Mortality/Risk": metrics including, for example, mortality rates, survival probabilities; "Reproduction potential": metrics including, for example, spawning, larval settlement; "Space Use": metrics including, for example, movement, flight patterns, home ranges, site fidelity; "Species population": metrics including, for example, abundance, density, structure, composition, biomass.*

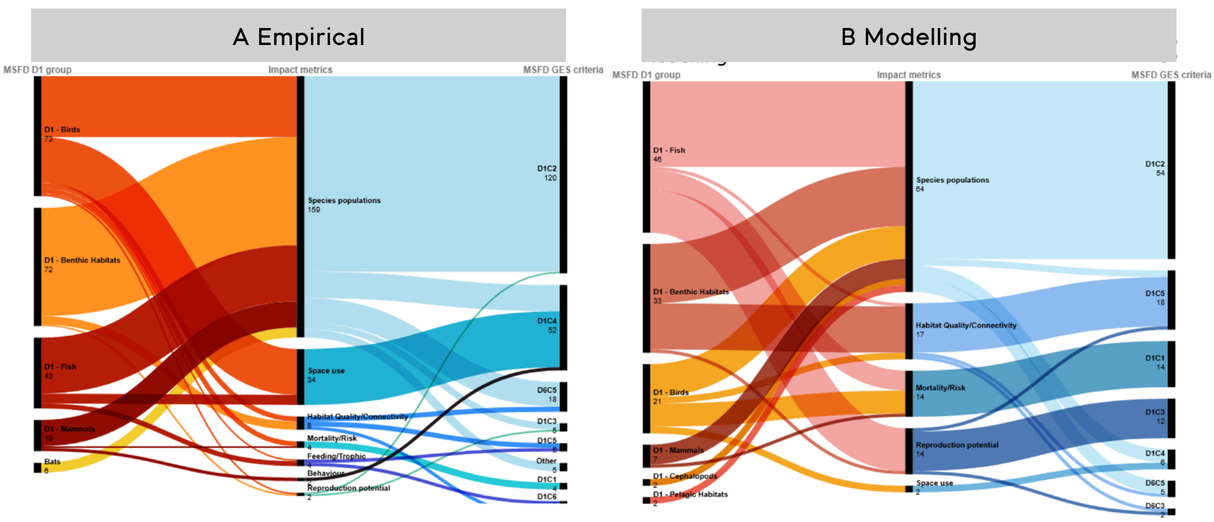


Figure 11: *Distribution of reported impact case studies (n = 301) (from the 102 articles) - by evidence type - showing the effects of OWF on marine biodiversity. The MSFD D1 groups studied are displayed on the left bar, with impact metric groupings shown on the middle bar, and MSFD GES criteria on the right. The numbers represent the total number of case studies. Category descriptions are the same as fig 9: NB Impact metrics categorical groups from left to right: "Behaviour": metrics including, for example, behavioural responses such as vocal communication, stress/vigilance levels, respiration; "Feeding/trophic": metrics including, for example, diet composition, stomach content; "Habitat Quality/Connectivity": metrics including, for example, habitat quality, grain size distribution, habitat disturbance; "Mortality/Risk": metrics including, for example, mortality rates, survival probabilities; "Reproduction potential": metrics including, for example, spawning, larval settlement; "Space Use": metrics including, for example, movement, flight patterns, home ranges, and site fidelity;, "Species population": metrics including, for example, abundance, density, structure, composition, biomass OWF measured impacts on biodiversity.*

Measured impacts of OWFs on D1 are described by the ecological compartment represented in the descriptor. In addition, evidence on bats was included as this taxonomic group is increasingly impacted by offshore wind farms (cf. Methodological framework).

D1- Birds

Laridae & Sternidae (Gulls and Terns): Black-legged kittiwake (*Rissa tridactyla*); Common gull (*Larus canus*); Great black-backed gull (*Larus marinus*); Herring gull (*Larus argentatus*); Lesser black-backed gull (*Larus fuscus*); Little gull (*Hydrocoloeus minutus*); Sandwich tern (*Thalasseus sandvicensis*); Little tern (*Sternula albifrons*)

Several species of gulls and terns exhibited divergent responses to offshore wind farms, varying by species and metric. For instance, Vanermen et al. (2015) reported up to a 9.5-fold increase in numbers of Herring gulls (*Larus argentatus*) at Bligh banks, while lesser black-backed gulls (Larus fuscus) were also found to be attracted to OWFs, with local densities increasing significantly near turbines. However, conversely, Brabant et al. (2015) showed that common, lesser black-backed, and herring gulls could suffer substantial yearly mortality (up to 14%) when modelled in high-turbine density scenarios. Corman & Garthe (2014) showed that lesser black-backed gulls flew at variable heights, though most recorded flights were below 20 m. A total of 89 % of recorded fixes were below 20 m above sea level, indicating an overlap between foraging flights and the rotor blade area of most operating wind turbines. GPS-tagged Lesser black-backed gulls were frequently found resting in the direct vicinity of the jacket turbine foundations or transformer platforms (Vanermen et al., 2020). Conversely, Mendel et al., 2014; noted post-construction decreases in overall abundance for little and the lesser black-backed gulls. Peschko et al. (2020) found significant density declines for Black-legged kittiwakes (up to 44.6%) during the breeding season within both 3 km and 20 km of turbines, suggesting seasonally variable avoidance. Likewise, Pollock et al. (2024) illustrated significant avoidance close to the turbines from 0 to 140m. Virgili et al. (2024) predicted the highest densities furthest from OWFs, supporting an avoidance effect. Flight height studies (Fijn et al., 2015; Fijn & Collier, 2022) of sandwich tern (*Thalasseus sandvicensis*) revealed frequent overlap with rotor-swept zones, with a mean height of ~13 m, suggesting potential collision risk, especially during foraging and transit flights.

Sulidae (Gannets): Northern Gannet (*Morus bassanus*)

Several studies (Busch et al., 2013; Mendel et al., 2014; Pollock et al., 2024; Vanermen et al., 2015; Virgili et al., 2024) describe seasonal or spatial variation in gannet abundance; abundance may peak in winter months (December–March), with juveniles in late summer. Declines in abundance after OWF construction were noted locally Mendel et al., 2014. Evidence indicates consistent avoidance of OWFs, suggesting partial displacement and associated habitat loss for these pelagic birds. Vanermen et al. (2015) reported an 85% reduction in Northern gannet (*Morus bassanus*) density within 0.5 km of the Bligh Bank OWF, indicating strong localised avoidance. Using collision risk modelling, Brabant et al. (2015) estimated annual gannet mortality of 8.1% at Bligh Bank, with projected collisions ranging from 0 to 3,455 birds per year, depending on turbine numbers and migration intensity. Pollock et al. (2024) found that juveniles spend more time in high-risk OWF zones than adults. Garthe et al. (2017a); Garthe et al. (2017b); Cleasby et al. (2015), Peschko et al. (2020), and Furness et al. (2018) provide evidence of gannets avoiding entering OWFs, especially within 250 m of turbines, and tend to fly higher (17.9 m) when inside OWFs than outside (14.4 m). However, flight heights generally remain low overall. Gannet foraging trips can range from 4 to over 500 km, overlapping with multiple OWFs; avoidance was observed in 89% of tracked individuals.

Gaviiformes (Lot tons / Divers): Divers (*Gaviidae spp.*); Loons (*Gavia spp.*)

Vilela et al. (2021) found no consistent trend in diver (*Gaviidae* spp.) abundance across their study area, though the lowest estimates occurred in 2008–2009, prior to OWF construction. In contrast, Mendel et al. (2019) documented strong spatial avoidance by loon species (*Gavia* spp.) following OWF development, with densities decreasing by 94% within 3 km of turbines and by 84% at 10 km. Birds aggregated in alternative areas, indicating large-scale displacement. Garthe et al. (2023) found strong and consistent evidence that loons (*Gaviidae* spp.) avoid offshore wind farms at large spatial scales; abundance declined by 92–99% within 1 km of OWFs and by 29–68% within 10 km. Indeed, significant reductions in density extended up to 12 km from turbine footprints, indicating extensive habitat displacement. Busch et al. (2013) estimated habitat loss between 5.4% and 12.2% for red-throated divers (RTD) (*Gavia stellata*), driven by their strictly coastal distribution, which overlaps with the placement of OWFs. Duckworth et al. (2022) highlighted the migratory behaviour of different RTD populations, noting that Finnish birds travel from the eastern Baltic through OWF-dense areas in the southern North Sea, making them particularly vulnerable. In contrast, Scottish and Icelandic populations may face lower exposure due to more limited migratory overlap with OWFs.

Alcidae (Auks): Common guillemot (*Uria aalge*); Razorbill (*Alca torda*)

Guillemots exhibit a generally negative spatial response to OWFs. Abundance was reported to decrease post-construction. Mendel et al. (2014) showed that the highest abundance was outside of wind farms. Vanermen et al. (2015) found strong avoidance of the Bligh Bank offshore wind farm (OWF) by auks, with common guillemot (*Uria aalge*) and razorbill (*Alca torda*) densities reduced by 71% and 64% respectively, within 0.5 km of the turbines. Similarly, Busch & Garthe (2016) estimated that OWFs in the Helgoland cluster could affect up to 146 guillemots during the breeding season, including 97 likely breeding adults, suggesting potential population-level impacts beyond local displacement. Likewise, Peschko et al. (2020) found significant post-construction declines in guillemot density around OWFs, with reductions of 63% in spring and 44% during breeding within 3 km, and 49% and 30% respectively, within 9 km. Likewise, Peschko et al. (2024) found that up to 68% of the guillemot population in the German North Sea will experience habitat loss.

Phalacrocoracidae (Cormorants and Shags): Cormorants (*Phalacrocoracidae sp*); European shags (*Phalacrocorax aristotelis*)

A comparatively little-studied group, Virgili et al. (2024) found that cormorant (*Phalacrocoracidae* spp.) abundance distribution is very coastal, with consistent year-round presence along the French and Belgian coasts. Grémillet et al. (2020) identified spatial overlap between the foraging areas of European shags (*Phalacrocorax aristotelis*) around Chausey, Normandy and zones of planned or operational OWFs. They report moderate risks of both collision and displacement for shag populations in the English Channel.

Waders (shorebirds): Eurasian curlew (*Numenius arquata*); Other non-pelagic shorebirds

Schwemmer et al. (2023a) outline that Eurasian curlews exhibited significantly lower flight altitudes across the Baltic Sea, and migration intensity peaked at night during spring. This nocturnal migration pattern, combined with lower flight altitudes, highlights potential periods of increased collision risk with OWFs. Schwemmer et al. (2023b) demonstrated that non-pelagic shorebirds did not exhibit significant changes in horizontal movement patterns in response to the OWFs.

D1 - Mammals

Harbour porpoises (*Phocoena phocoena*):

Concerning species population changes, Nabe-Nielsen et al. (2014) found that OWFs caused a 10.4% reduction in mean harbour porpoise population size. While Dähne et al. (2013) observed a sharp drop in porpoise density during pile-driving in 2009, followed by a return to pre-construction levels by 2010. Longer pile-driving durations were associated with increased porpoise displacement. Virgili et al. (2024) predicted harbour porpoises prefer offshore waters over coastal areas, with higher densities beyond 20 km from shore. Densities were lowest in summer (~0.1/km²) and highest in spring (3–5/km²). Porpoises tended to avoid OWF areas during construction but returned to similar abundance levels once operational. Scheidat et al. (2011) reported increased harbour porpoise activity during the operational period, with porpoise-positive minutes (PPM) rising between 28% and up to 160%. Encounter durations were longer, and waiting times were significantly reduced compared to baseline measurements. Echolocation activity exhibited seasonal peaks in winter, with a decline in summer. Teilmann & Carstensen (2012) reported a 43%

drop in porpoise clicks per minute during construction and operation periods. Echolocation activity initially declined but showed significant recovery in later operational periods, especially period 2 (January 2005–December 2005), i.e., 2 years after construction. The study highlights a clear negative impact during the construction phase. Skov & Thomsen (2008) found that harbour porpoise acoustic activity is strongly influenced by tidal-driven upwelling and vertical water movements. Porpoises tend to aggregate in small, dynamic upwelling zones (under 10 km) linked to seabed features and tidal currents. Their study highlights the importance of fine-scale oceanographic processes over broad physical conditions in shaping the distribution of porpoises. Regarding mortality and injury, Bailey et al. (2010) found peak noise levels of 205 dB re 1µPa at 100 m from pile-driving, with auditory injury limited to within 100 m and strong avoidance expected beyond 20 km. Sound levels dropped significantly beyond 10 km due to absorption. Soft-starts helped mitigate impacts by allowing animals to move away; however, behavioural responses varied with exposure duration and context, rather than noise level alone. Kastelein et al. (2013) found that exposure to underwater noise had a behavioural impact on Harbour Porpoises; noise levels ranging from 130 to 154 dB led to increased respiration rates, with test values consistently higher than baseline measurements. At 136 dB re one µPa and above, the mean respiration rates differed significantly from baseline levels, indicating a physiological response to the sound exposure.

Dolphins: Bottlenose dolphin (*Tursiops truncatus*)

Potlock et al. (2023) observed no significant change in the occurrence of two dolphin species before and after OWF construction at gravity-based foundations. However, a significant decline was observed during construction, suggesting disturbance caused by pile-driving. Likewise, Bailey et al. (2010) reported that pile-driving generates high sound levels with potential for auditory injury to bottlenose dolphins within 100 m, and disturbance up to 50 km. Raoux et al. (2017) modelled ecosystem responses to offshore wind farms for a number of trophic groups and found that the biomass of bottlenose dolphins (*Tursiops truncatus*) increased after OWF construction.

Seals: Harbour (*Phoca vitulina*) and Grey seals (*Halichoerus grypus*)

Similarly, Raoux et al. (2017) provided some indication that both harbour (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) may benefit indirectly from increases in prey biomass. For example, Atlantic cod was consumed approximately 3.5 times more by seals according to the model prediction after the wind farm implantation. However, harbour seal biomass decreased from 6.73×10^{-4} to 1.89×10^{-3} gC m^{-2} yr^{-1} after construction, while grey seal biomass increased from 2.68×10^{-4} to 8.73×10^{-4} gC m^{-2} yr^{1} in the model.

Bats: (NB not formally included in the MSFD; for the current report, we describe OWF impacts, cf. sections "Methodological framework")

Six case studies were included, focusing on bats and studying either species populations (related to D1C2) or space use (related to D1C4) (Figure 10). Brabant et al. (2020) show that activity of *Pipistrellus* spp. and *Pipistrellus nathusii* - observed across 20 nights, with a total of 151 bat calls recorded (Rydell & Wickman, 2015)– had a distinct vertical stratification: at calls at low altitude (6 m above sea level) averaged 20.3 per night, while high-altitude calls (93 m) averaged only 2.3 per night. This suggests that *P. nathusii* are predominantly active near the sea surface, with limited use of higher altitudes. Therefore, OWFs pose a collision risk for migrating bats. Further, flight patterns appear to follow a strong coastal preference (Rydell & Wickman, 2015). In both 2017 and 2020, detections—measured using "positive ten-minute" (DP10) contact intervals—were significantly more frequent nearshore than offshore. In 2017, the average DP10/night was only 0.03 versus 0.67 at the nearshore locations. In 2020, nearshore activity was 3.4 to 24 times higher than that at offshore locations, indicating a preference for coastal concentration during migration periods. Lagerveld et al. (2021) showed that the probability of bat presence decreased with increasing wind speed; activity was generally highest in calm sea conditions. Migration was especially pronounced in early September. Lagerveld et al. (2023) underscore the possibility of a spatial gradient in bat presence, with western OWF areas showing higher bat activity than those in the South, East, or northern parts of the North Sea. This suggests regional differences in migration routes or habitat preferences, which may have implications for the siting of OWFs. Rydell & Wickman (2015) emphasise that certain OWF locations appear to attract bats, potentially due to artificial lights or food availability.

D1 - Reptiles

No papers were retrieved covering the impacts of OWF expansion on marine turtles. Even though the potential effects of OWFs on sea turtles remain unclear in the North and Baltic Sea, researchers and stakeholders suspect sea turtles may experience effects similar to those experienced by marine mammals (e.g., collision risks, acoustic effects on hearing and behaviour).

D1 - Fish

The presence of offshore wind farms can modify fish distributions and composition by attracting species to artificial structures and reducing the abundance of species that rely on soft-bottom habitats (Buyse et al., 2022; Cornelis et al., 2024; Stenberg et al., 2015). Cod, for instance, is strongly attracted to structures like pipes and scour protection, where increased complexity enhances habitat suitability. They also exhibit strong site fidelity, particularly in summer, though some remain year-round (Berges et al., 2024; Reubens et al., 2013). Additionally, cod near hard substrates show dietary shifts and greater prey diversity (Gimpel et al., 2023).

Wind turbine foundations support higher fish densities than surrounding waters, providing vertical structures that enhance food availability by delaying the transport of plankton due to small-scale turbulence. Zooplankton-dependent species, such as two-spotted gobies, are abundant around turbines, particularly near ladders and cable drums (Andersson & Öhman, 2010). OWFs often overlap critical habitats, such as flatfish spawning grounds (2–16% of settlers originate from OWF areas) (Barbut et al., 2020) and may further enhance spawning connectivity for species with pelagic larvae by linking natural and artificial hard substrates (Van Der Molen et al., 2018).

Experimental exposure to pile-driving sound (L_E = 206 dB re 1 $\mu Pa^2 s$ for an exposure to 100 strikes) showed no significant increase in mortality for common sole larvae within the first 7 days post-exposure (Bolle et al., 2012). The effects of OWFs on fish vary across their developmental stages, yet most research focuses on adults during operation. Large-scale OWFs and their impact on migrating fish species need further study. Multi-use marine parks incorporating OWFs have different implications for fish stocks, requiring more empirical evaluation (Burkhard et al., 2011).

D1 - Cephalopods

One paper (Raoux et al., 2017) with two modelling-type case studies was retrieved covering the impacts of OWF expansion on cephalopods. The authors studied biomass data (gC m−2 year−1) and divided it into two groups: "Bentho-pelagic cephalopods" composed of *Loligo sp.* and *Allotheuthis sp.*, and "Benthic cephalopods" composed of *Sepia officinalis* (case studies were coded under Species populations; see → Figure 10). A small increase in biomass for both groups appeared after construction of the OWF.

D1 – Pelagic habitats

The same paper, Raoux et al. (2017), measured mean annual biomasses of zooplankton and phytoplankton from data collected from monitoring the quality of water bodies in the Bay of Seine. No changes in biomass were found for either group before and after the construction of the OWF, according to the model results.

D1 - Benthic Habitats

OWFs introduce artificial hard substrates that change benthic community composition, from soft-sediment species to biofouling communities. There is limited information on whether OWFs promote the spillover of benthic species, such as edible crab or lobster, contributing to population increases. Underwater noise and vibrations can affect benthic invertebrates, but their effects remain largely understudied (Van Der Molen et al., 2018).

Evidence indicates that the development of OWFs initiates a complex and sequential transformation of benthic ecosystems. During the construction phase, seabed preparation, pile driving, and cable installation cause localised disturbances, sediment resuspension, and habitat removal, resulting in significant benthic species mortality. Despite these immediate impacts, post-construction recovery tends to occur rapidly. Coates et al. (2016) documented that macrobenthic communities in the North Sea recolonised affected areas within months to years, primarily through opportunistic pioneer species.

In the long term, the introduction of hard substrates, such as turbine foundations and scour protection, represents the most significant ecological shift. These artificial structures function as reef habitats, supporting dense assemblages of sessile epifauna, including *Mytilus edulis* and barnacles, which increase local biomass and structural complexity (Krone et al., 2013). The resultant transition from soft-bottom infauna to hard-substrate epifauna enhances local biodiversity while simultaneously altering native community composition (Gutow et al., 2014).

Such habitat modifications also drive ecosystem-level changes. Ecological modelling by Raoux et al. (2017) suggests that OWFs enhance secondary production by favouring suspension-feeding organisms, thereby modifying energy transfer pathways and benthic–pelagic coupling. The exclusion of bottom trawling within OWF boundaries further promotes the recovery of sensitive benthic species and modifies community structure (Roach et al., 2018). Moreover, OWFs can facilitate species dispersal; Vodopivec et al. (2017) demonstrated that offshore structures provide settlement substrate for jellyfish polyps (*Aurelia spp.*) through expanded hard-bottom benthic habitat.

Recent studies addressing the decommissioning phase indicate that management decisions at this stage will strongly influence the severity of impacts on benthic biodiversity. Spielmann et al. (2023) showed that partial removal strategies, such as retaining scour protection or cutting foundations above the seabed, preserve critical hard-substrate habitat and minimise biodiversity loss, whereas complete removal causes substantial declines in associated epibenthic macrofauna. Given the current paucity of empirical data, further research is urgently needed to inform evidence-based decommissioning frameworks that balance ecological integrity with technical feasibility.

Cumulative effects

Modelling studies have evaluated cumulative collision risks for seabirds under large-scale offshore wind development scenarios. Simulations projecting up to 10,000 turbines in the North Sea indicate that species such as gannets (*Morus bassanus*), black-legged kittiwakes (*Rissa tridactyla*), and lesser black-backed gulls (*Larus fuscus*) may face significant population-level consequences. These impacts could result in an additional yearly mortality rate ranging from 0.5% to 9%, along with increased energetic costs due to prolonged flight path avoidance, particularly during critical migration periods (Bailey et al., 2010; Skov & Thomsen, 2008; Teilmann & Carstensen, 2012).

The construction and operation of multiple OWFs within the same geographical area can have cumulative effects on marine species, such as the harbour porpoise (*Phocoena phocoena*). An example of these impacts is the Nysted OWF and the adjacent Rødsand 2 OWF, located approximately 3 km apart.

Long-term monitoring of the Nysted OWF revealed a significant decline in harbour porpoise echolocation activity following its construction, with a gradual but incomplete recovery over the following years. This suggests a slow habituation process or potential changes in habitat quality. In contrast, studies assessing the cumulative impact of Nysted and Rødsand 2 OWFs during their operational phases found no significant additional negative effects on the presence of harbour porpoises. The porpoise activity levels within the wind farm areas were comparable to those in reference areas.

Habitat Loss & Displacement

- **Seabirds:** Species like loons, guillemots, and gannets experience displacement, reducing habitat availability and forcing them to relocate, sometimes into less suitable areas. Guillemots are affected up to 19.5 km from OWFs in the German North Sea (Garthe et al., 2023; Mendel et al., 2019; Schwemmer, Mercker, et al., 2023).
- **Decline in herring abundance** - a primary diet of Little tern (*Sternula albifrons*) - following monopile installation (Garthe et al., 2023; Mendel et al., 2019; Schwemmer, Mercker, et al., 2023) during herring spawning seasons, suggesting that construction noise may interfere with fish recruitment and ultimately reproductive success in terns (Perrow et al., 2011).
- **Marine Mammals & Fish:** OWFs alter spatial distributions of species like plaice (*Pleuronectes platessa*) and cod, leading to seasonal shifts and habitat fragmentation (Furness et al., 2018).

Disturbance from Noise & Human Activity

- **Marine Mammals:** Noise from piling activities substantially reduces detections of harbour porpoises up to 10–15 km away, and further when noise mitigation systems (NMS) are absent (Fijn et al., 2015).
- **Fish & Invertebrates:** OWFs serve as artificial reefs but may alter community compositions and introduce competitive pressures, affecting species connectivity and dispersal patterns (Rebke et al., 2019).

Changes in Prey Availability & Food Webs

- **Predatory Fish:** OWFs attract species like cod due to artificial reef effects, potentially altering food web dynamics and increasing competition (Van Der Molen et al., 2018).
- **Plankton & Benthic Communities:** OWFs facilitate the spread of hard-bottom fauna into soft-bottom areas, influencing ecosystem structure and biodiversity patterns (Mercker et al., 2021).

Identified knowledge gaps

Major knowledge gaps concern the impacts of OWFs on turtles (no studies were retrieved on reptiles). Likewise, only one study covered impacts on cephalopods. Concerning marine mammals, no studies on whales were retrieved by our Scoping review, a single study on seals, two on dolphins - the evidence base is skewed towards porpoises. From an MSFD standpoint, these are species groups that merit greater attention. Concerning seabirds, a tendency across primary literature is to focus on gannets, gulls and terns while auks, cormorants, shags and shorebirds appear much less studied. Concerning benthic habitats, the effects of decommissioning, including the potential loss of hard substrate and associated communities, represent a major unknown. Regarding so-called "reef effects," they may temporarily attract fish. However, long-term ecosystem functioning and service provision remain poorly understood.

Conclusion for Descriptor 1

Concerning seabirds, many species appear to avoid immediate turbine areas, with collision risks generally highest for gulls and terns. Consistent spatial displacement has been reported across seasons and distances, with potential implications for breeding populations of auks. Habitat displacement is also likely to influence foraging behaviour and spatial use patterns across broad areas for gannets.
Collision risks for bats remain a concern, particularly for Pipistrellus species that migrate across seas and typically fly at turbine height. For marine mammals and fish, responses to noise disturbance are evident: porpoises tend to move away from piling sites, whereas some fish species show a degree of resilience.

The impacts of OWFs on benthic habitats are mixed. During the construction phase, seabed communities experience substantial physical disturbance. Over the long term, hard turbine structures and scour protections become colonised by sessile organisms such as mussels and barnacles. Although this colonisation is often described as a potential artificial reef effect, its overall contribution to ecosystem functioning remains uncertain. The development of mussel-dominated communities can significantly alter benthic habitats, modifying the composition and abundance of native species. This process replaces natural soft-sediment communities with artificial hard-bottom habitats, potentially favouring non-indigenous and reef-associated species over those dominating sediment environments. Such introductions of new habitats and species can generate cascading effects throughout the marine food web, influencing both demersal (bottom-dwelling) and pelagic (open-water) species.
Despite increasing research, substantial knowledge gaps persist regarding long-term, cumulative, and population-level effects. The interactions among multiple OWFs, climate change stressors, and species adaptation strategies remain poorly understood. Future research should prioritise multi-species monitoring, the development of effective mitigation measures, and adaptive management approaches to ensure that OWFs contribute to biodiversity conservation while minimising ecological risks.

4.1.2 Descriptor 2. Non-indigenous species

Author: Federica Pace
Reviewer: Jan-Claas Dajka

Context

MSFD defined Non-indigenous species (NIS) as those species introduced outside their natural past or present range, which might survive and reproduce. Some of the NIS can be harmless, with negligible impacts on native species. Other NIS can be invasive, with the potential to alter the native community composition and cause local population extinction, resulting in long-lasting impacts that threaten biodiversity and ecosystem services.

D2 is assessed through 3 criteria:

- **D2C1 – Primary:** The number of non-indigenous species which are newly introduced via human activity into the wild, per assessment period (6 years).
- **D2C2 – Secondary:** Abundance and spatial distribution of established non-indigenous species, particularly of invasive species, contributing significantly to adverse effects on particular species groups or broad habitat types.
- **D2C3 – Secondary:** Proportion of the species group or spatial extent of the broad habitat type, which is adversely altered due to non-indigenous species, particularly invasive non-indigenous species.

The purpose of the SSS is to review the state of knowledge on the impacts of fixed offshore wind parks on the introduction of non-indigenous species.

Impact of offshore wind energy expansion on non-indigenous species

Literature searches and screening process

Very few studies are available on the topic of introducing non-indigenous species in relation to offshore wind farm development. The literature search (see search strings in → Annexe 3)

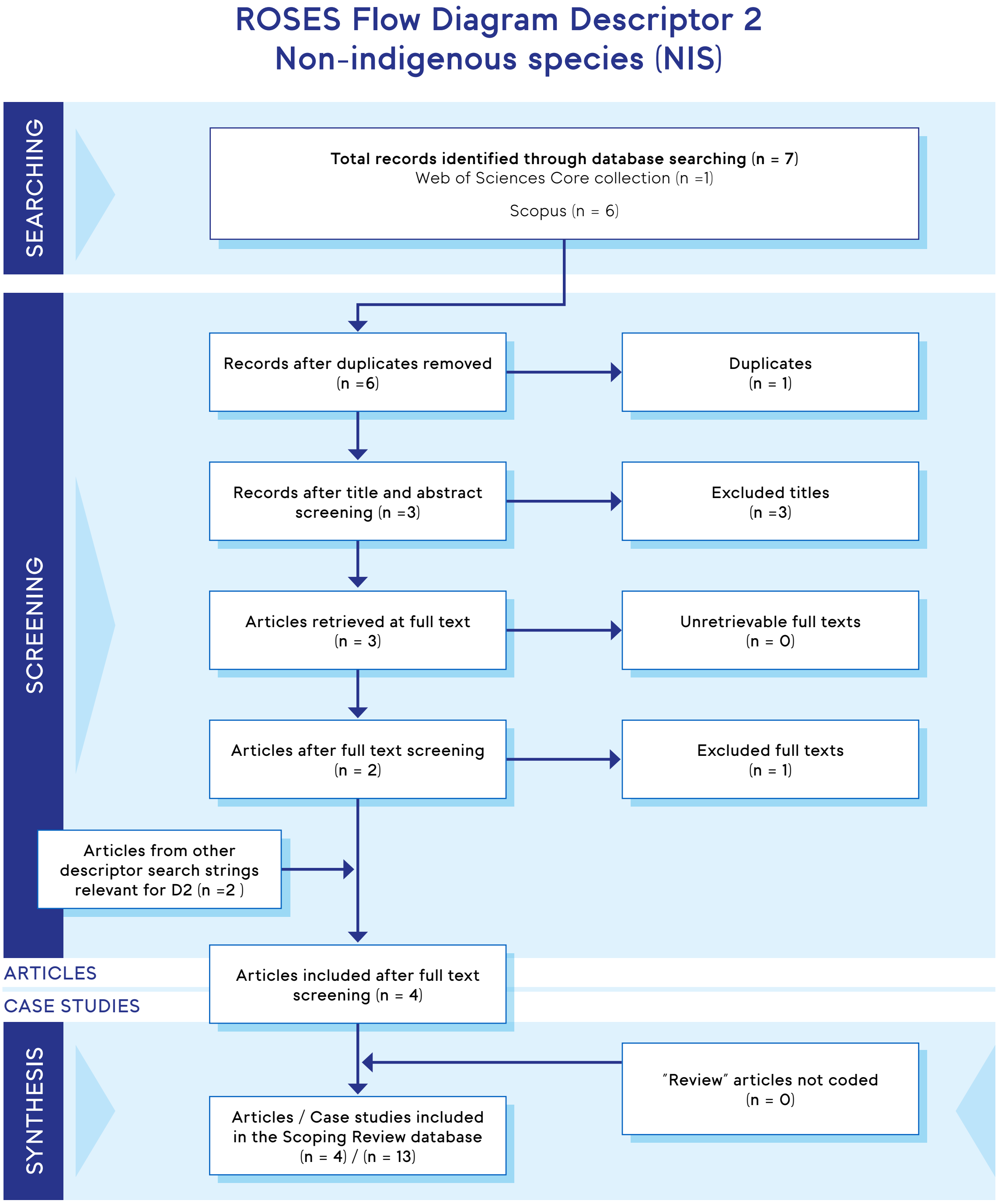


Figure 12: ROSES flow diagram illustrating the screening process and selection of literature for descriptor D2.

returned only seven articles. Only two of them met the screening criteria and were retained for extraction, while two additional papers were identified from other descriptor searches following a review of the full papers (see → Figure 12).

Publication trends, data collection duration, and study design

The studies retained for extraction in relation to D2 included two observational studies from data collected in 2010 and two predictive modelling study that referred to the period between 2013 and 2015 (→ Figure 13). Only one study considered the decommissioning phase while the others the operational phase of a wind farm.

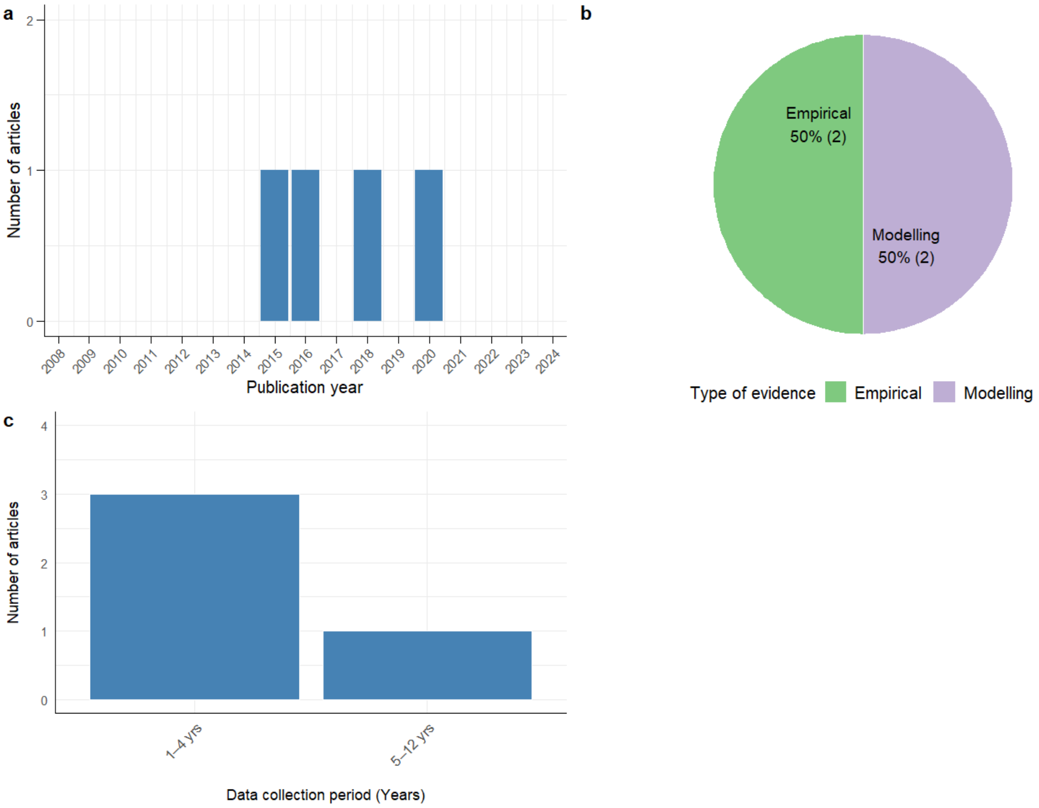


Figure 13. Distribution of retained articles for descriptor 2. Panel (a) shows the number of documents published per publication year. Panel (b) illustrates the distribution of the type of evidence. Panel (c) illustrates the number of articles per data collection period.

Geographical distribution of the evidence base

The studies retained for extraction were limited to only four; therefore, the geographical coverage is very limited, as shown in the map (→ Figure 14). All papers referred to the Greater North Sea.

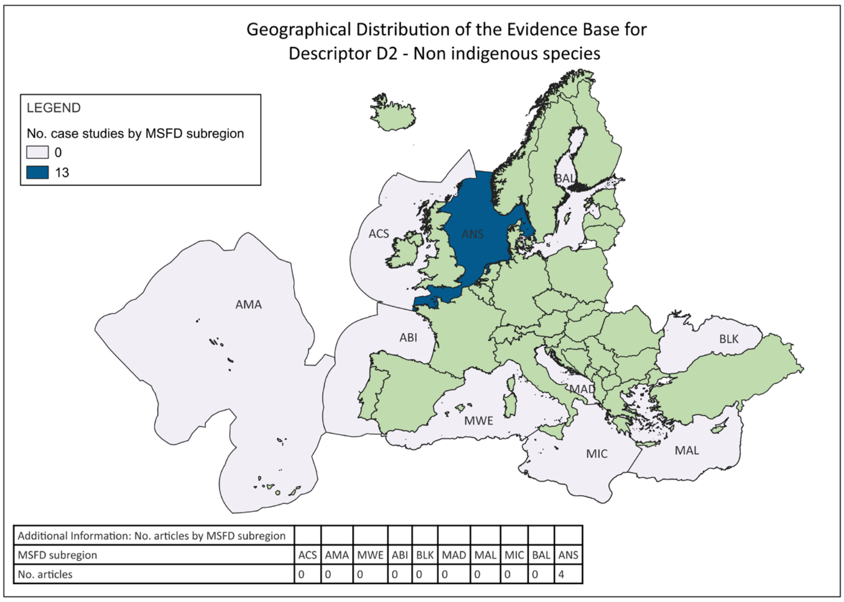


Figure 14. Number of case studies by MSFD subregion for descriptor 2. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD).

Methodological approaches and trends in study designs

Impacts and cumulative impacts are measured using a few study designs, namely control-intervention studies (→ Figure 15). Most articles (3) have short data collection periods (1-4 years).

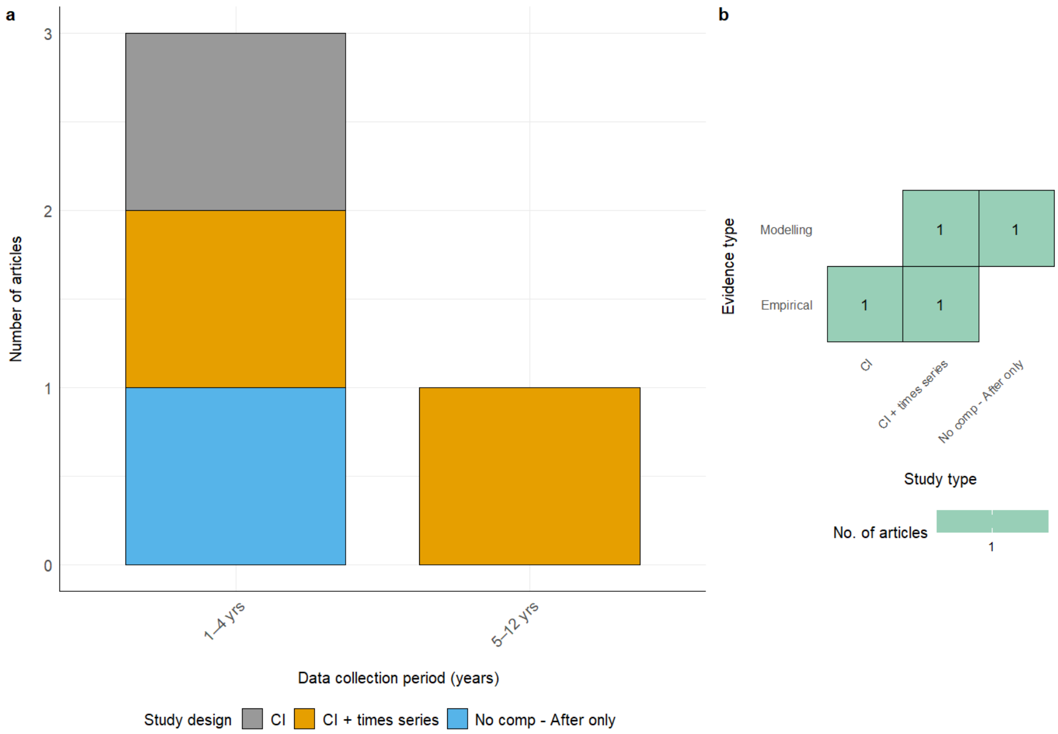


Figure 15. Distribution of evidence type, study design, and data collection periods for descriptor 2. Number of articles by data collection period and study design type (panel a), and number of articles by evidence type and study design (panel b).

OWF measured impacts on non-indigenous species

OWF may introduce NIS through the movement of vessels and/or equipment. In particular, the introduction of man-made structures, such as wind turbine foundations, creates new habitats in predominantly sandy environments, facilitating the settlement of non-indigenous species with little competition from native species. Many NIS are early colonisers, rapidly taking advantage of the new substrates to establish and expand their populations.

Moreover, wind farm structures act as'stepping stones'that allow NIS to expand their range by providing intermediate habitats between their original locations and new areas.

Studies found that several species of benthic macrofauna (invertebrates) are associated with wind turbine foundations (De Mesel, 2015) and that offshore structures and natural substrates serve as important spawning and settling sites for various sedentary species with pelagic larval phases (Van de Molen, 2018). NIS species varied in abundance and with time from installation. Within the wind farm, 64% of the samples held one or more non-indigenous species and 11 non-indigenous species were found in total (9 on steel and 4 on rock dump) (Coolen, 2020).

The predictive modelling studies showed that:

- habitat suitability for the Japanese skeleton shrimp (Caprella mutica) is improved in the splash zone of the foundations, allowing the species to develop and reside (Coolen, 2016).
- Non-indigenous species percentage was higher in the intertidal zone (most frequent non-indigenous species was the tunicate Diplosoma listerianum), which is in line with observations by De Mesel et al. (2015).

The findings suggest that the presence of man-made structures can enhance connectivity between naturally occurring hard substrate features, thereby influencing marine community dynamics.
Long-term monitoring and studies in various areas and habitats are necessary to enhance our understanding of this descriptor (see → Figure 16).

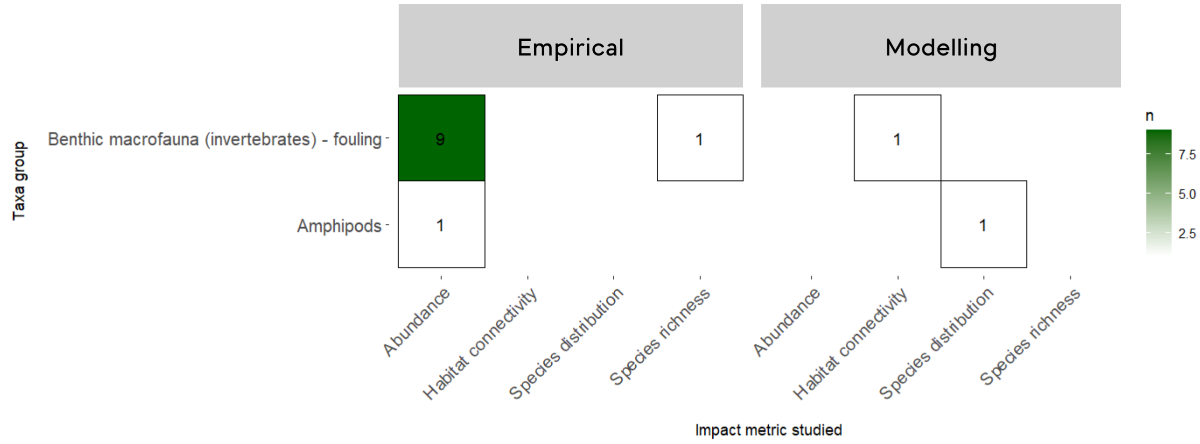


Figure 16. Heat map illustrating the number of case studies (n = 13 from 4 articles) by D2 group and impact metric used to study the effects of offshore wind farm expansion. The colour intensity represents the quantity of evidence, with darker shades indicating higher evidence levels. The y-axis corresponds to the studied taxa, and the x-axis corresponds to our impact metrics groupings. NB Impact metrics as reported by authors are presented.

Identified knowledge gaps

There is a lack of literature available on D2 in relation to offshore wind farm developments, making it difficult to draw general conclusions. However, NIS introduction is also regulated through IMO/ OSPAR and other international organizations that act alongside the MSFD. Evidence of potential impacts for this descriptor may also be searched in the grey literature (excluded from this work) in relation to maritime industries such as shipping.
Considering that the literature reviewed only applies to the Greater North Sea region, a significant gap exists in understanding the potential for the introduction and settlement of NIS in other regions, such as the Mediterranean Sea. Furthermore, life stages beyond the operational phase have not been addressed thus far.

Cumulative effects

Given the limited literature available on the topic, it is not possible to comment on the cumulative effects associated with this descriptor.

Conclusion for Descriptor 2

OWFs facilitate the introduction and spread of NIS. The artificial reef effect and stepping stone connectivity enable opportunistic NIS to colonise wind farm structures, particularly in intertidal and shallow subtidal zones.
Significant knowledge gaps exist, as research is currently limited to two North Sea studies on a single species during the operational phase. Long-term, multi-region, and decommissioning phase studies are necessary to fully assess the impacts of OWFs on NIS dispersal.

4.1.3 Descriptor 3. Commercial fish and shellfish

Author: Ina M. Sieber
Reviewer: Aurore Maureaud

Context

Commercial fish and shellfish populations play a vital role in marine ecosystems and the global seafood industry. Descriptor 3 of the MSFD emphasises the need for these populations to remain within **safe biological limits**, ensuring a balanced age and size distribution that reflects a **healthy stock**. However, **overfishing and unsustainable fishing practices** threaten the stability of marine resources, leading to stock depletion, habitat destruction, and unintended bycatch of sensitive species.

The Common Fisheries Policy (CFP) serves as the primary regulatory framework for managing EU fisheries, but greater alignment with environmental legislation—especially the MSFD—is crucial to achieving GES. The criteria for measuring **Descriptor 3 (D3): Commercial fish and shellfish** under the MSFD focus on assessing the sustainability of fish and shellfish populations based on their biological status, fishing pressure, and population structure. These criteria align with ensuring GES and preventing overfishing. The following key criteria for measuring D3 exist:

- **D3.1: Population Biomass (Stock Size) within Safe Biological Limits** refers to the spawning stock biomass (SSB) that must be at or above levels that ensure long-term reproductive capacity. Stocks should be maintained within sustainable limits to prevent collapse.
- **D3.2: Fishing Mortality (F) at Sustainable Levels**, including the rate of fish removal due to fishing (F), should not exceed the Fishing Mortality at Maximum Sustainable Yield (FMSY). Additionally, overfishing occurs when F exceeds FMSY, resulting in stock depletion.
- **D3.3: Age and Size Distribution of the Population** refers to a healthy population structure, with a balanced **distribution of different age and size classes** (proportion of mature fish in the stock, mean size of fish in catches, proportion of large fish **indicating a well-functioning population**).

If all three criteria are met (D3.1, D3.2, and D3.3), the fishery is considered sustainable and resilient. If one or more criteria are failing, the stock may be at risk, requiring stricter fisheries management measures to ensure long-term sustainability.

Impact of offshore wind energy expansion on commercial fish and shellfish

Literature searches and screening process

For this descriptor, a total of 47 articles were retained from a pool of 206 retrieved articles after the screening process, including contributions from social and environmental sciences (→ Figure 17). Eight review articles were not coded. Evidence was summarised from 39 articles. Note that studies were excluded following the criteria described in the Methods section.

ROSES Flow Diagram Descriptor 3
Commercial fish and shellfish

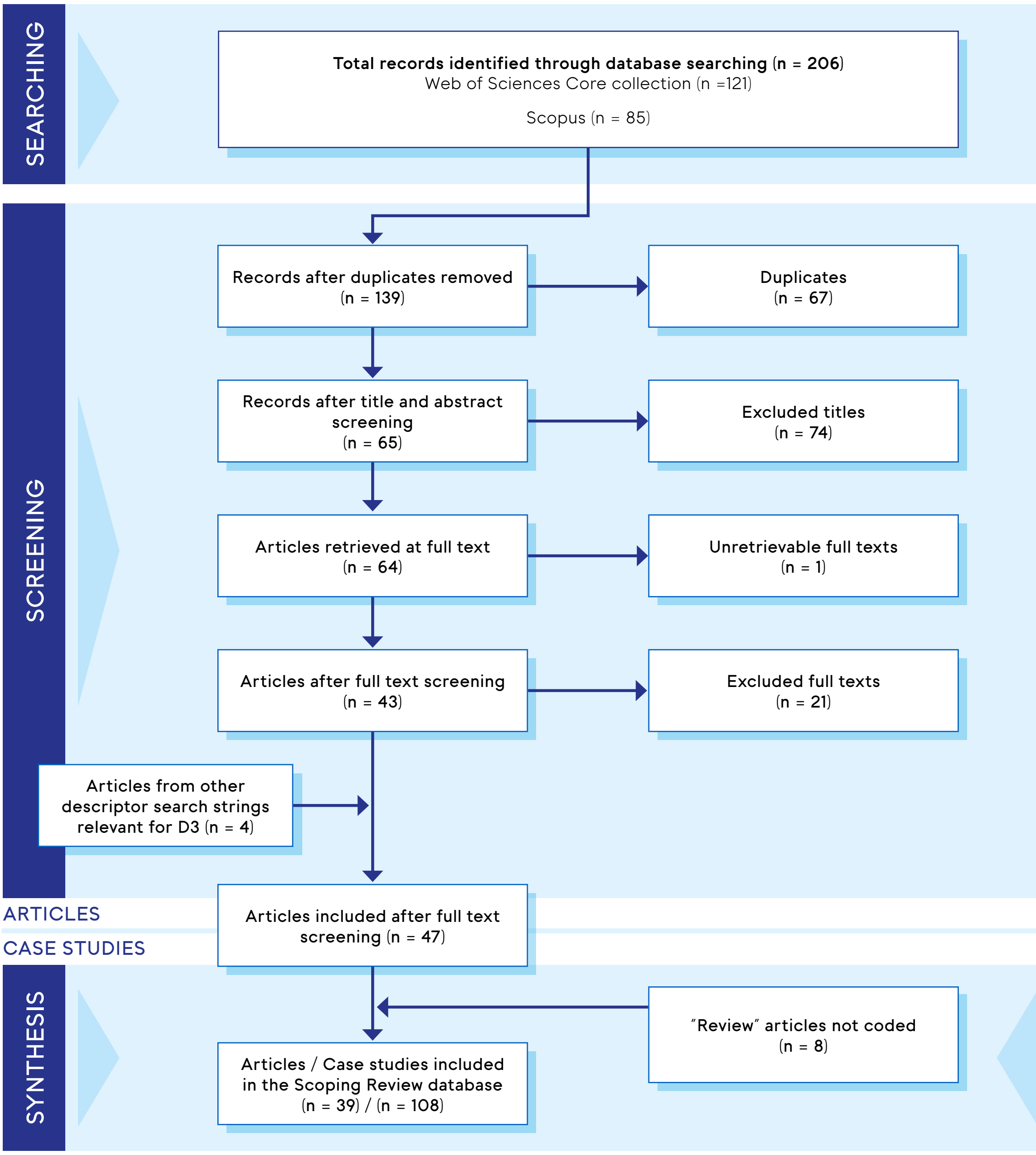


Figure 17. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D3.

Publication trends and data collection duration

Temporal coverage covered: 2010-2024 (→ Figure 18)
Study type: Almost 51% of studies are empirical, utilising observational methods and line fishing, as well as other sampling methods, to measure fish stocks. 28% of the studies were modelling studies, based on stochastic, Bayesian, and predictive biophysical modelling and scenario building, and 4% were based on experiments.

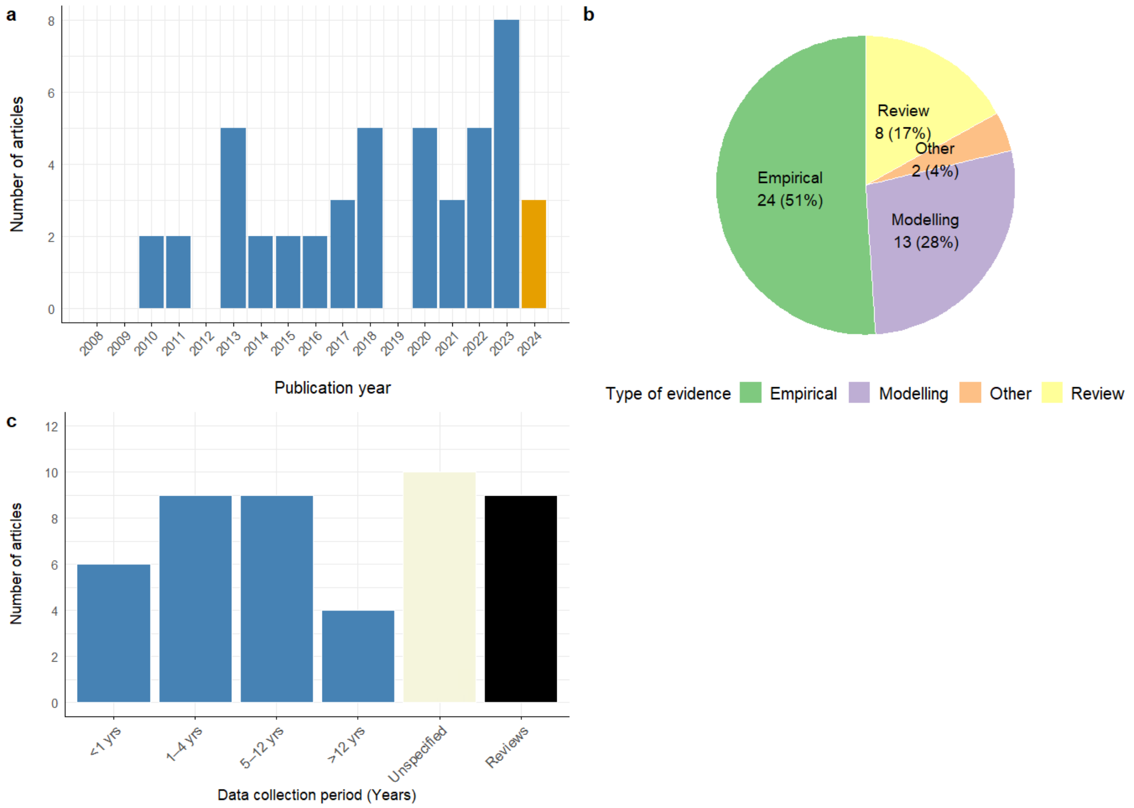
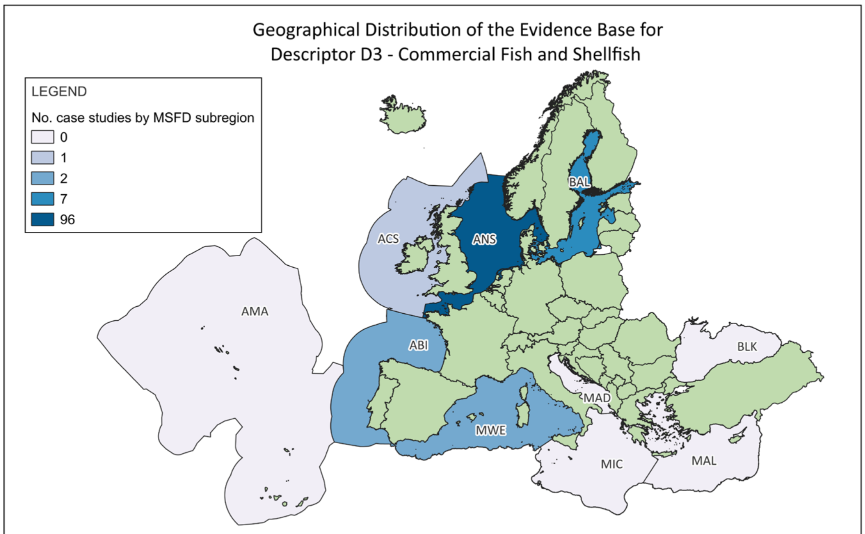


Figure 18. Distribution of retained articles for descriptor 3. Panel (a) shows the number of documents published per year (please note that 2024 (orange bar) is not a complete year: literature searches were undertaken in October). Panel (b) illustrates the distribution of the type of evidence. Panel (c) illustrates the number of articles per data collection period. Review studies were then excluded from the extraction (see Methods). Please note that in panel (c), "Reviews" (black bar) corresponds to Review type evidence (i.e., where data collection periods were not applicable); "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection period.

Geographical distribution of the evidence base

Geographic areas covered: northeast Atlantic (92%) with studies on the Greater North Sea prevailing, the Baltic Sea (5.7%) and the northeast Atlantic Ocean and Black Sea (1.1%) (→ Figure 19).



Additional Information: No. articles by MSFD subregion										
MSFD subregion	ACS	AMA	MWE	ABI	BLK	MAD	MAL	MIC	BAL	ANS
No. articles	1	0	2	1	0	0	0	0	4	35

Figure 19. Number of case studies by MSFD subregion and number of articles by MSFD subregion [ ] for descriptor 3. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD)

OWF characteristics reported

Nearly 38% of the studies focus on monopile turbines, while the remainder involve tripods (6.3%), jackets (2.6%), and gravity foundation structures (2.6%). Thirty-six per cent of case studies included unspecified characteristics. The articles consider the planning, operation and installation life cycle stages of OWFs.

Ecological compartment represented

Literature, based on the number of case studies, on D3 covers fish (74%; 80 case studies) as well as shellfish, i.e., benthic macrofauna fouling only (6%), and seabed only (17%, → Figure 20). Numerous commercial fish and shellfish species are studied, including Atlantic cod (12%), plaice (7%), common sole (3.5%), European lobster (3.5%), and blue mussel (*M. edulis*, 3.5%), among others.

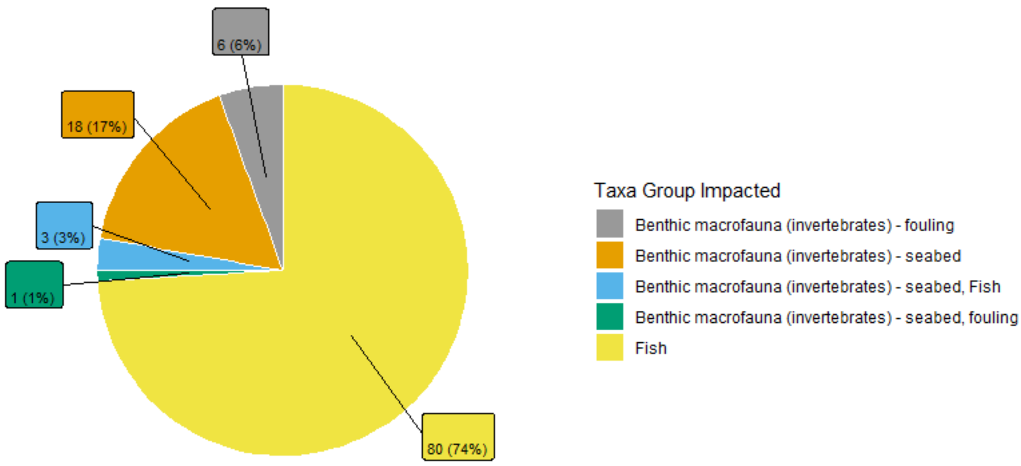


Figure 20. Number (and %) of different commercial species studied in OWF impact studies. Note that some articles studied multiple taxa simultaneously (see "Benthic macrofauna (Invertebrates) - seabed, fish"). This refers to the seabed, and fish are studied simultaneously. "Benthic macrofauna (Invertebrates) - seabed, fouling". Likewise, seabed fouling species were studied simultaneously.

Ecological Impacts

Habitat alteration: Changes in the seabed structure due to turbine foundations affect fish spawning and nursery grounds (Barbut et al., 2020)

Artificial reef effect: The introduction of monopile structures and related hard substrate in the sandy habitat of the southern North Sea attracted fish and crab species and altered the behaviour of the fish. The monopile fixed bottoms of the wind farm can function as an artificial reef, especially in the Greater North Sea (Werner et al., 2024; Qu et al., 2023; Van Hal et al., 2017). Wind farm structures are predicted to increase benthos biomass, and as a consequence, provide more resources for fish benthic feeders, as well as top predators such as sole and cod (Raoux et al., 2018). As a result, OWFs attract species of economic interest, such as plaice or lobster (shown in greater catch rates around monopiles (Roach et al., 2018; Werner et al., 2024; Wright et al., 2020), potentially altering local ecosystems and predator-prey dynamics (Raoux et al., 2018). This reef effect is dependent on the type of wind turbine, which can result in considerably higher catch rates of cod around monopiles with rock protection compared to monopiles with sandbag protection or around jacket foundations, as observed in the Great North Sea (Werner et al., 2024).

Noise pollution: Construction noise (such as pile driving) and operational noise may disturb commercial fish behaviour, including larval orientation, spawning, and migration patterns. During the installation of OWFs, changes in fish migration patterns occur (Barbut et al., 2020; Buyse et al., 2022). Readers can look for further insights on noise effects in the D11 SSS for more information.

Synergies between OWF and Marine Protected Areas (MPAs): can be beneficial due to their artificial reef effect and changes in fish spawning and migration patterns, which extend beyond commercial fish species, creating refugia and conservation effects (Bastardie et al., 2015; Werner et al., 2024). However, real edge effects due to changes in fisheries intensity or 'spillover' from the wind farms could not be shown (Vandendriessche et al., 2015).

Economic Impacts

Reduced fishing areas: Exclusion zones and restrictions within wind farm areas may limit access to traditional fishing grounds (Qu et al., 2023). Within the closed areas, the reduced fishing pressure can lead to an increase in fish biomass (Püts et al., 2023).

Increased competition: The closure of marine areas may displace fishing effort to surrounding areas. Such effort displacement can redirect the fishing pressure to other localities (Bastardie et al., 2015). Displaced fishers may be forced into smaller or more congested areas (Püts et al., 2023), increasing competition for resources. Studies show competition for fish stocks (Dinmore et al., 2003; Hilborn et al., 2004; Hiddink et al., 2006), as cited in Bastardie et al. (2015), and potential conflicts for deploying various fishing techniques at the same location (e.g., mobile vs. static gears) (Bastardie et al., 2015).

Potential changes in catch rates: Some species may thrive in wind farms (e.g., those benefiting from artificial reefs such as Atlantic cod (Berges et al., 2024), while others may decline due to the presence of predators, potentially impacting fisheries yields.

New economic opportunities: The limited fishing activities around OWFs may present an opportunity for alternative income sources, such as aquaculture (Jansen et al., 2016), as well as providing services for wind farm construction, maintenance, or scientific monitoring.

Social and Regulatory Impacts

Conflicts between stakeholders: Tensions between fishers, planning authorities, wind energy developers, and policymakers, tourism over space use, access rights, and compensation have been described (Stelzenmüller et al., 2022).

Shifts in local economies: Coastal communities that depend on fisheries may experience economic and employment shifts, necessitating adaptation strategies.

Unclear compensation frameworks: Financial mitigation measures for affected fishers vary across regions and may not fully address long-term losses.

Cumulative effects

Trophic shifts: The artificial reef effect of hard substrate of OWFs may contribute to a conservation effect (Werner et al., 2024) for many species, such as mussels (Kotta et al., 2020) or sole (Berkenhagen et al., 2010). The restriction of areas for fishing may increase predator species (e.g., cod, lobster) around OWFs, altering prey populations (Raoux et al., 2018), and changing fish communities on a small scale. For example, the introduction of new species, such as gold skinny wrasses or grey triggerfish, has been reported in the literature (Van Hal et al., 2017). Such introductions modify and can potentially alter existing food webs (see more on this theme in the D4 SSS).

Fisheries redistribution: Fishing activities can be mutually exclusive with other demands for space, such as shipping or OWFs or conflict with the management objective of a spatial restriction, such as MPAs (Bastardie et al., 2015), leading to closure of highly productive marine areas. This can lead to the displacement of fishing activities, such as trawling, and result in the upscaling of fisheries intensity in other areas (Bastardie et al., 2015). In turn, this can cause unexpected ecosystem changes in areas outside OWFs increasing pressure on certain species and leading to secondary ecological consequences (Raoux et al., 2018).

Spillover and edge effects: The absence of fishing (usually forbidden within wind farms) may increase biodiversity and the abundance of benthopelagic and benthic species that use OWFs for shelter and as feeding grounds, with potential, positive spillover effects (Mavraki et al., 2021). Scenarios suggest beneficial economic effects from OWFs through the artificial reef effect, as fishermen have access to increased fish resources (Qu et al., 2023). However, while OWFs provide refuge to some commercial species, spillover effects to adjacent areas remain uncertain. If predators concentrate in OWFs, it could impact surrounding prey species beyond the wind farm boundaries (Halouani et al., 2020). However, the work of Vandendriessche in the Belgian North Sea did not observe strong edge effects due to changes in fisheries intensity or 'spillover' outside of OWFs (Vandendriessche et al., 2015).

Links to Multiple Pressures and State descriptors

- **D1 - Biodiversity.** OWFs alter habitats and species behaviour (e.g., reef effects, noise disturbance), impacting overall marine biodiversity, including non-commercial species.
- **D4 - Food webs** OWFs can modify predator-prey relationships and trophic interactions through artificial reef effects and spatial displacement of species, influencing energy flow and food web structure.
- **D6 - Seabed integrity** OWFs physically alter the seabed (e.g., through foundation structures and cable burial), affecting benthic habitats critical for demersal and benthic commercial species.

Identified knowledge gaps

There are important knowledge gaps and remaining questions raised from the scoping review. For instance, limited research on **how impacts accumulate or diminish over time**, e.g., do benefits from artificial reefs persist or fade? Do negative effects from habitat loss recover? (Halouani et al., 2020). There are unclear **trade-offs between OWF expansion and fisheries management**: how will OWF-related spatial restrictions interact with long-term sustainable fishing quotas? Uncertainty remains about amplification effects: do displaced fisheries intensify pressure elsewhere, leading to stock depletion? Insufficient evidence on **how multiple OWFs interact at a regional scale**—do they create large-scale ecological shifts or only localised effects? Additionally, there appears to be a lack of standardised monitoring and methodology, with a need for harmonised approaches. Specifically, studies use varied methodologies (e.g., extractive sampling vs. modelling), making cross-study comparisons difficult. Consistent approaches may be needed to replicate monitoring activities across regions and OWFs (Vandendriessche et al., 2015). Furthermore, short-term studies are more prevalent; therefore, **longitudinal monitoring programs** are needed to capture cumulative impacts, such as spillover or edge effects. There is insufficient experimental research (**only 1% of studies**), limiting causal understanding of how commercial fish species are affected by OWFs. It remains unclear how **seasonal** or **interannual variations** (e.g., climate change-driven shifts) influence OWF impacts on fisheries and commercial species. Additionally, longitudinal studies that prove spillover effects and catch rates locally are lacking. Finally, the impacts of OWF on fisheries go beyond a change in the abundance of a few key species. As such, there is a need for the integration of social sciences, and continuous monitoring and stakeholder engagement are required to balance wind energy expansion with the sustainable management of fisheries, thereby meeting the demand for fish.

Conclusion for Descriptor 3

OWFs impact commercial fish and shellfish through habitat modification, as wind turbines create novel artificial reefs on hard substrate (see more in the SSS on D6) and noise disturbance (see more in the SSS on D11). Commercial species are affected through changes in adult species spatial distribution, larval distribution, spawning, and catch rates due to the exclusion of fishing grounds and changes in fishing practices in OWFs. Such exclusion can cause spill-over and edge effects at the local scale. These cumulative impacts interact temporally and spatially and can lead to ecosystem changes, altered predator-prey dynamics, and fisheries displacement, although large-scale spillover effects have not yet been demonstrated. Key knowledge gaps include the long-term cumulative impacts on multiple OWFs, interactions with other marine activities (e.g., aquaculture) and socio-economic impacts on fisheries, which require improved monitoring, cross-sectoral research and integrated policy approaches under the MSFD.

4.1.4 Descriptor 4. Food webs

Authors: Daniela Limache de la Fuente, Ute Jacob
Reviewer: Aurore Maureaud

Context

According to the Good Environmental Status (GES), descriptor 4 (D4) focuses on marine food webs, emphasising that all their ecological components should be present at natural levels of abundance and diversity to ensure the long-term sustainability and reproductive capacity of species. The GES outlines four criteria for D4:

- **D4C1 and D4C2 (primary criteria):** they focus on maintaining the diversity within trophic guilds and the balance of total abundance between them, respectively.
- **D4C3 and D4C4 (secondary criteria):** they address the size distribution of individuals and the productivity of trophic guilds, with the latter supporting D4C2 if needed.

All criteria require Member States to establish threshold values through regional or subregional cooperation.

Offshore Wind Farms (OWFs) can influence these marine food webs through various direct and indirect pathways, potentially affecting all trophic levels—from primary producers to top predators and therefore disrupting the structure and functioning of the food webs.

Impact of offshore wind energy expansion on food webs

Literature searches and screening process

The flow diagram below (→ Figure 21) illustrates the literature selection process for descriptor D4. A total of 63 records were initially identified through searches in the WOSCC and Scopus repositories (see Annexe 3 for search strings). After removing duplicates, 44 records remained for screening. At the title and abstract screening stage, 29 records were excluded, leaving 15 full-text documents for further screening. Of these, four were excluded. An additional five relevant records were identified from other literature searches. 4 review papers were not coded. Thus, 12 relevant articles were included in the SSS.

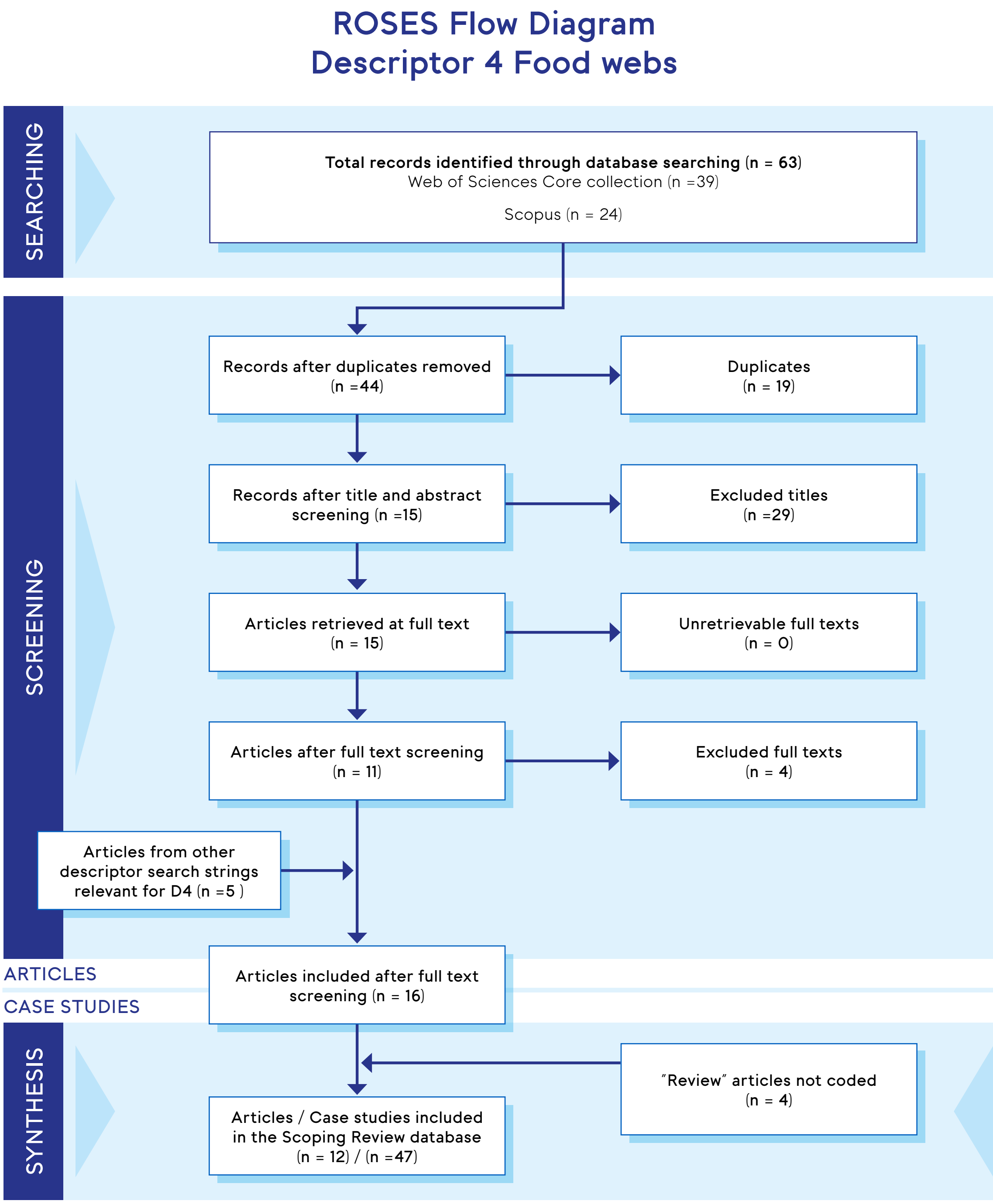


Figure 21. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D4.

Publication trends, data collection duration, and study design

Temporal coverage covered: 2008 – present (→ Figure 22)

Study type: 100% peer-reviewed journal articles, with 31% providing empirical evidence and 44% presenting findings from predictive modelling.

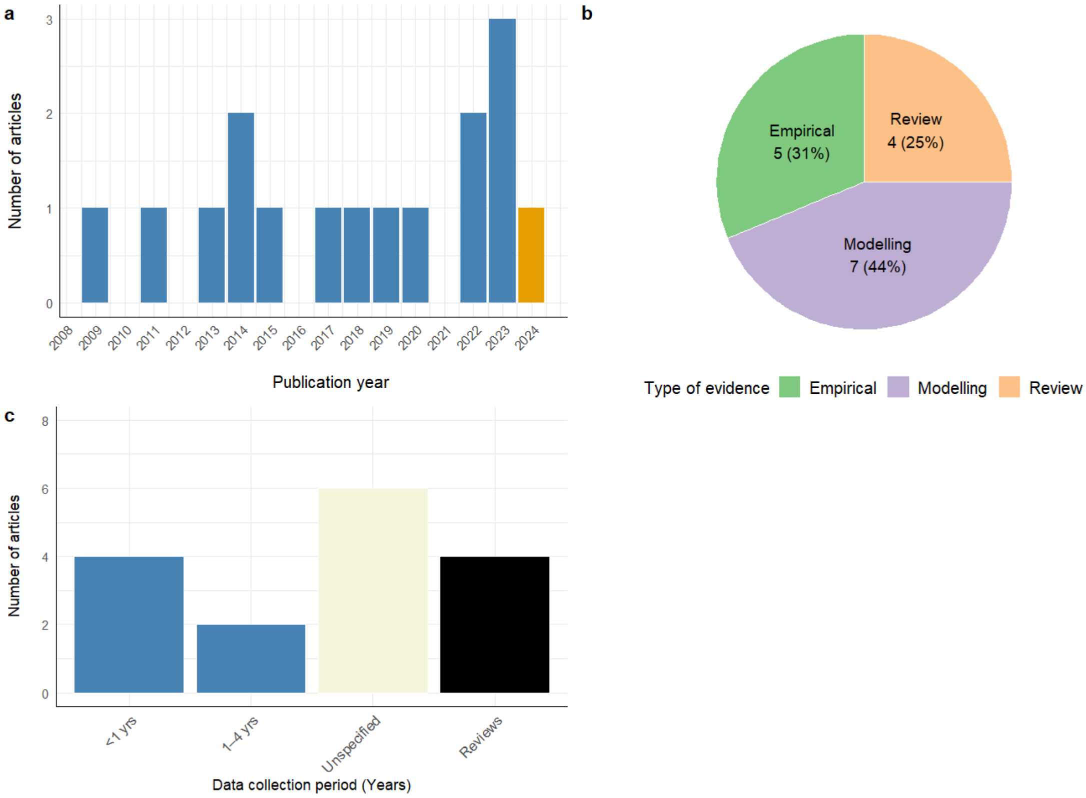
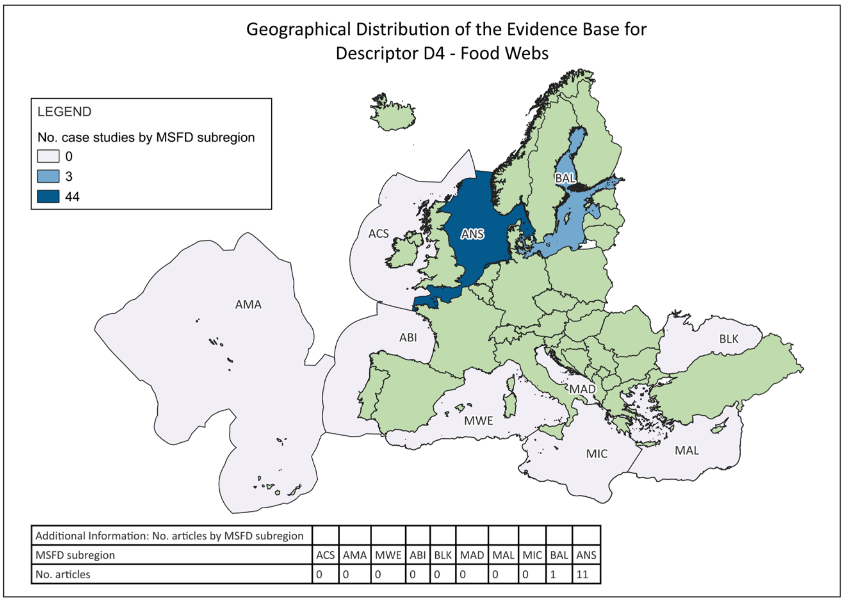


Figure 22. Distribution of bibliographic information for descriptor 4. Panel (a) shows the number of documents published per publication year (please note that 2024 (orange bar) is not a complete year: literature searches were undertaken in October). Panel (b) illustrates the distribution of the type of evidence. Lastly, panel (c) illustrates the number of articles per data collection period. Note that in panel (c), "Reviews" (black bar) corresponds to Review type evidence (where data collection periods were not applicable); "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection period.

Geographic areas covered:

Most studies focus on the Greater North Sea, including the English Channel and Kattegat (ANS), accounting for 86% of the case studies (44 in total). The remaining 14% (3 case studies) corresponds to the Baltic Sea (BAL, see F→ Figure 23).



Additional Information: No. articles by MSFD subregion										
MSFD subregion	ACS	AMA	MWE	ABI	BLK	MAD	MAL	MIC	BAL	ANS
No. articles	0	0	0	0	0	0	0	0	1	11

Figure 23. Number of case studies and number of articles by MSFD subregion for descriptor 4. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD).

OWF characteristics reported

Nearly 50% of the studies focus on monopile turbines, while the remainder involve jacket and gravity foundation structures. The articles consider the operation and installation life cycle stage of OWFs.

Impacts of offshore wind farms on the food web

Demersal fish aggregation and energy intake:

The impacts of OWFs on marine food webs are diverse. Research on demersal fish species, such as Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*), reveals the aggregation of these species around OWF artificial hard substrates, suggesting that these structures serve as feeding grounds, supporting sufficient energy intake without evidence of competition between the species. The values of Cellular Energy Allocation (CEA) (>1) suggest higher food intake than required for metabolism, allowing energy availability for growth and reproduction (De Troch et al., 2013). The diel feeding behaviour of Atlantic cod indicates foraging activity both during the day and night, suggesting they remain in the OWF area continuously. Cod predominantly occurs at low ambient light levels (dusk and dawn), likely balancing foraging efficiency with predation risk (Reubens et al., 2014).

Biomass changes and trophic functioning following OWF construction:

Comparative modelling scenarios before and after OWF construction show significant increases in biomass across demersal fish, pelagic species, and invertebrates (Halouani et al., 2020; Raoux et al., 2017).

Furthermore, fishing closures within OWFs can lead to localised biomass increases and potential spillover benefits for adjacent fishing areas. However, these effects are spatially limited and highly dependent on species mobility and local ecological conditions. Overall, the literature indicates that areas adjacent to the OWF instalments exhibit increased biomass, while bordering zones show no significant change, and areas further away display a decrease in biomass (Halouani et al., 2020).

Blue mussels (*Mytilus edulis*) on OWF foundations exhibit enhanced biomass growth due to higher food availability in surface layers and protection from predation (Maar et al., 2009). Mussel aggregations create "hot spots" that affect ecosystem dynamics through the ingestion of plankton, the excretion of ammonium, and the production of faecal pellets. The increased ammonium excretion by mussels enhances the growth rates of phytoplankton (Maar et al., 2009).

Other studies using Ecopath with Ecosim (EwE) modelling to simulate food web dynamics over a 30-year period following OWF construction suggest a substantial shift in ecosystem structure. In the pre-construction scenario, the food web appeared to be wasp-waist controlled, with pouting (*Trisopterus luscus*) functioning as a key species at intermediate trophic levels. In contrast, in the post-construction scenario, the system shifted toward greater detritivory, driven by an increase in mussel biomass, which became a dominant energy pathway (Raoux et al., 2017). Comparisons of total ecosystem activity (i.e., biological and biochemical processes), omnivory (generalist feeding), and nutrient recycling showed increases after OWF construction. Specifically, Ecosystem Efficiency (EE) rose by 5%, and the Detritivory/Herbivory (D/H) ratio increased by 18.8%, with detritivory and herbivory reaching 1.5 times and 1.2 times their pre-OWF levels, respectively (Raoux et al., 2017). Offshore wind turbine structures have a significant influence on benthic communities and local food webs. Sampling at various distances (15–200 m) from turbine bases reveals significantly higher macrobenthic abundance and species richness in close proximity to the structures compared to more distant zones. The influence on benthic assemblages was observed up to ~200 m from the foundations. The hard substrates and biodeposition from fouling organisms enhance food availability and habitat complexity. This likely feeds into higher trophic levels, potentially benefiting demersal fish and other consumers (Coates et al., 2014).

Wind wakes effects on primary production:

Studies demonstrated that wind wakes from OWFs can lead to significant changes in primary production and oxygen levels in the North Sea, potentially impacting food web dynamics (Daewel et al., 2022).

Noise disturbance and food webs:

The foraging success of little terns (*Sterna albifrons*) declined due to a reduction in prey (herrings), likely linked to intense monopile installation noise during winter spawning (Perrow et al., 2011).

Cumulative effects

The cumulative qualitative impact assessments show OWFs structures lead to an increase in hard-substrate benthic growth (reef effect), which combined with the reduction in fishing pressure due to restricted access, alters local biodiversity and trophic interactions. Additionally, climate change amplifies these ecological shifts, impacting key commercial species such as sole (Solea solea), cod, and king scallops (Pecten maximus) (Raoux et al., 2017).

Cascading effects from OWFs and links to multiple pressures and state descriptors

- **D3 (Fisheries):** OWFs can create artificial reefs, attracting certain fish and invertebrate species, which may alter predator-prey dynamics and local energy flows. Such changes can cascade through the food web, altering species composition and trophic interactions, ultimately affecting biodiversity across multiple levels. Overfishing can alter predator-prey dynamics and energy flows. Additionally, reductions in fish stocks can lead to trophic cascades affecting the entire food web.
- **D1 (Biodiversity):** OWFs influence phytoplankton dynamics through changes in hydrodynamics, light availability, and nutrient cycling, potentially shifting primary production. Such changes can cascade through the food web, altering species composition and trophic interactions, ultimately affecting biodiversity across multiple levels.
- **D5 (Eutrophication):** OWFs can modify local currents and nutrient dispersal, influencing the extent and distribution of eutrophication. This can favour opportunistic species and disrupt natural food web balances, amplifying or dampening plankton blooms and altering energy transfer within ecosystems.

Identified knowledge gaps

Very little is known about the impacts of OWFs on food webs, as reflected in the limited number of publications available and scoped for this descriptor. Regarding knowledge gaps, we highlight areas where further research is needed to fully understand the OWFs' effects:

- **Spatiotemporal scales of influence and impacts:** Although the "reef effect" is recognised within OWF areas and adjacent zones, the spatial extent of OWF-induced food web impacts remains unclear. Can these effects propagate beyond local scales and influence broader regional ecosystems?
- **Spillover effects and regional-scale impacts:** Zones of spillover effects (positive, neutral, or negative) are observed around OWFs, but uncertainty remains regarding the cause of these patterns and their extent. Could OWFs create regional-scale changes in fish stock distributions, impacting fisheries beyond their direct zone of influence?

- **Changes in trophic guild structure and composition:** Research on the impacts of OWFs on the composition, relative abundance, and size distribution of individuals in the trophic guilds remains limited. Some key questions include: Do artificial structures favour specific functional groups (e.g., sessile filter-feeders) while disadvantaging others (e.g., soft-sediment specialists)? How do they impact horizontal and vertical food web diversity? Does fishery exclusion lead to competitive release or trophic cascades (e.g., increased predation on benthic invertebrates)? How do OWF-driven shifts in predation or competition affect the size distribution of species within guilds, and what does this mean for the ecosystem energy flow?
    - **Impacts on Higher Trophic Levels:** while direct biomass increases (e.g., fish aggregation, mussel growth) are observed, how do these affect higher trophic levels (e.g., marine mammals, seabirds, apex predators)? How does increased prey availability alter predator-prey dynamics? How does this lead to shifts in foraging behaviour, efficiency, or reproductive success?
    - **Noise Pollution and Trophic Dynamics:** the long-term effects of OWF-related noise pollution on fish food webs are insufficiently studied. In particular, the potential influence of noise on predator-prey dynamics (e.g., through altered foraging efficiency or anti-predator responses). These effects could trigger new risks in trophic cascades.
- **Biogeochemical feedbacks (e.g., mussel colonisation):** The accumulation of mussels around OWFs increases ammonium excretion, causing phytoplankton growth. Questions remain about whether this benefits filter feeders (e.g., zooplankton, bivalves, fish larvae) or disrupts natural nutrient cycling and food web stability.

Conclusion for Descriptor 4

OWFs affect marine food webs by increasing biomass through artificial reef effects, enhancing nutrient cycling, and altering species distributions. While they create new habitats and indirectly reduce fishing pressure, they also introduce ecological disturbances, such as noise pollution and habitat disruption, which can cause potential trophic imbalances. Further knowledge is needed to evaluate long-term ecosystem shifts, spillover effects, and interactions with climate change to ensure the integrity of marine food webs under OWF expansion.

4.1.5 Descriptor 5. Eutrophication

Author: Margaret Kadiri
Reviewer: Jan-Claas Dajka

Context

Assessment of Good Environmental Status: In relation to D5, MSFD considers that 'good environmental status is achieved when ↗ „Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algal blooms and oxygen deficiency in bottom waters". Following the definition given by a dedicated MSFD ↗ Task Group Report on descriptor 5, eutrophication is „a process driven by enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, leading to: increased growth, primary production and biomass of algae; changes in the balance of organisms; and water quality degradation. The consequences of eutrophication are undesirable if they appreciably degrade the ecosystem health and/or the sustainable provision of goods and services."

Below is the list of the criteria and indicators for D5 assessment.

- **D5C1 – Primary:** Nutrient concentrations are not at levels that indicate adverse eutrophication effects. The threshold values are as follows: (a) in coastal waters, the values set in accordance with Directive 2000/60/EC; (b) beyond coastal waters, values consistent with those for coastal waters under Directive 2000/60/EC. Member States shall establish those values through regional or subregional cooperation.
- **D5C2 – Primary:** Chlorophyll concentrations are not at levels that indicate adverse effects of nutrient enrichment. The threshold values are as follows: (a) in coastal waters, the values set in accordance with Directive 2000/60/EC; (b) beyond coastal waters, values consistent with those for coastal waters under Directive 2000/60/EC. Member States shall establish those values through regional or subregional cooperation.
- **D5C3 – Secondary:** The number, spatial extent and duration of harmful algal bloom events are not at levels that indicate adverse effects of nutrient enrichment. Member States shall establish threshold values for these levels through regional or subregional cooperation.
- **D5C4 – Secondary:** The photic limit (transparency) of the water column is not reduced due to increases in suspended algae to a level that indicates adverse effects of nutrient enrichment. The threshold values are as follows: (a) in coastal waters, the values set in accordance with Directive 2000/60/EC; (b) beyond coastal waters, values consistent with those for coastal waters under Directive 2000/60/EC. Member States shall establish those values through regional or subregional cooperation.
- **D5C5 – Primary (may be substituted by D5C8):** The concentration of dissolved oxygen is not reduced, due to nutrient enrichment, to levels that indicate adverse effects on benthic habitats (including on associated biota and mobile species) or other eutrophication effects. The threshold values are as follows: (a) in coastal waters, the values set in accordance with Directive 2000/60/EC; (b) beyond coastal waters, values consistent with those for coastal waters under Directive 2000/60/EC. Member States shall establish those values through regional or subregional cooperation.
- **D5C6 – Secondary:** The abundance of opportunistic macroalgae is not at levels that indicate adverse effects of nutrient enrichment. The threshold values are as follows: (a) in coastal waters, the values set in accordance with Directive 2000/60/EC; (b) should this criterion be relevant for waters beyond coastal waters, values consistent with those for coastal waters under Directive 2000/60/EC. Member States shall establish those values through regional or subregional cooperation.
- **D5C7 – Secondary:** The species composition and relative abundance or depth

distribution of macrophyte communities achieve values that indicate there is no adverse effect due to nutrient enrichment, including via a decrease in water transparency, as follows: (a) in coastal waters, the values set in accordance with Directive 2000/60/EC; (b) should this criterion be relevant for waters beyond coastal waters, values consistent with those for coastal waters under Directive 2000/60/EC. Member States shall establish those values through regional or subregional cooperation.

- **D5C8 – Secondary (except when used as a substitute for D5C5):** The species composition and relative abundance of macrofaunal communities achieve values that indicate that there is no adverse effect due to nutrient and organic enrichment, as follows: (a) in coastal waters, the values for benthic biological quality elements set in accordance with Directive 2000/60/EC; (b) beyond coastal waters, values consistent with those for coastal waters under Directive 2000/60/EC. Member States shall establish those values through regional or subregional cooperation.

Current background status: In 2023, approximately 2,632 km^2 of EU marine waters were classified as 'eutrophic'. A smoothed 4-year moving average analysis indicates a ↗ stable trend in eutrophication levels between 2018 and 2023. The four marine regions of Europe vary in their sensitivity to nutrient enrichment and eutrophication due to differences in their natural characteristics. In the Baltic Sea region, for example, more than 97% was assessed as eutrophic in 2011–2016. Despite efforts to reduce nutrient inputs over the past decades, eutrophication remains a persistent issue in European seas. While some regions, such as the northeast Atlantic, show signs of recovery, achieving a GES remains a challenging goal.

Impact of offshore wind energy expansion on eutrophication

Literature searches and screening process

The diagram below (→ Figure 24) illustrates the literature identification and screening process. As shown in Figure 24, the literature search yielded 55 records, of which 40 were screened after duplicates were removed. At the title and abstract screening, 23 were excluded. Seventeen were retrieved for screening, of which eight were excluded. One additional record considered relevant for D5, retrieved from other searches (i.e., a unique literature search was conducted per descriptor), was included. After excluding review papers during the data extraction stage, eight relevant papers were included in the SSS.

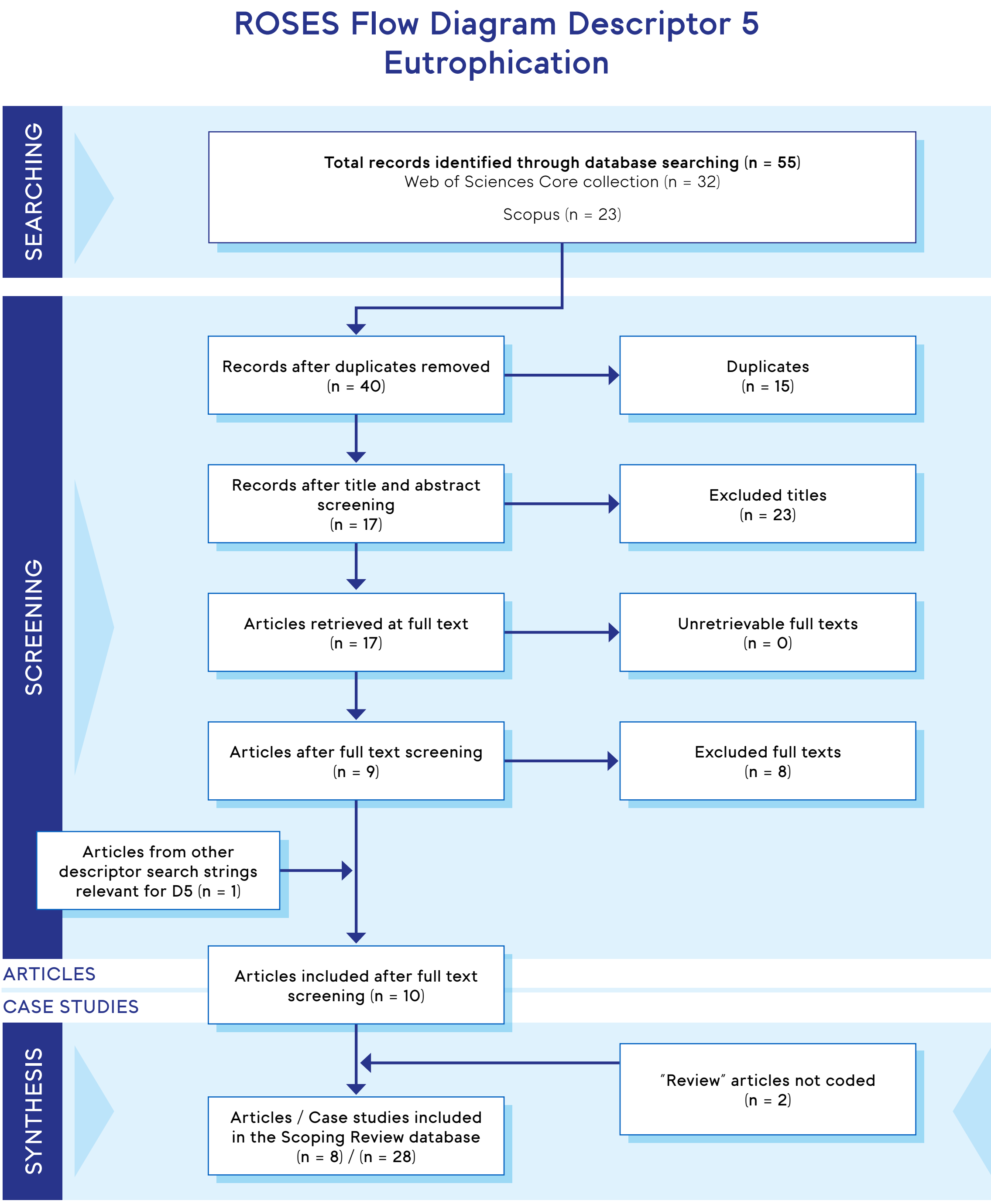


Figure 24. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D5.

Publication trends and data collection duration

Temporal coverage covered: 2015-2021 (→ Figure 25)

Study type: 100% peer-reviewed journal articles, with 40% of articles reporting empirical evidence, 40% of articles reporting findings from predictive modelling.

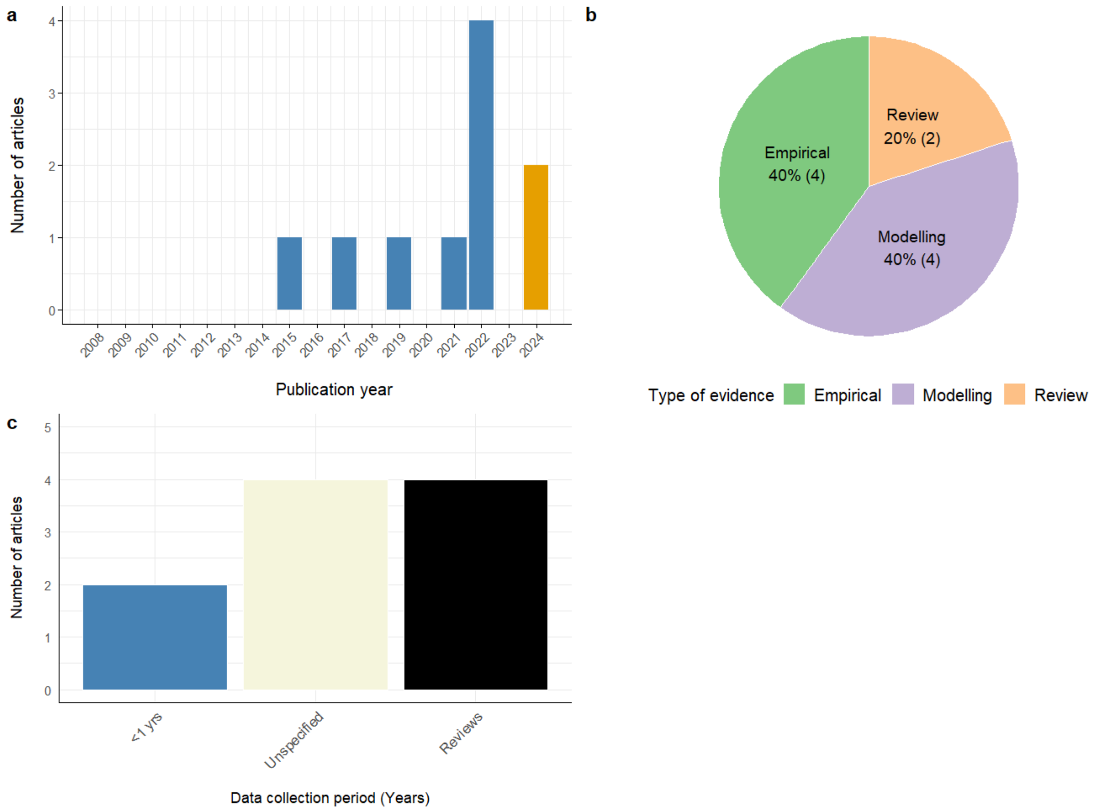
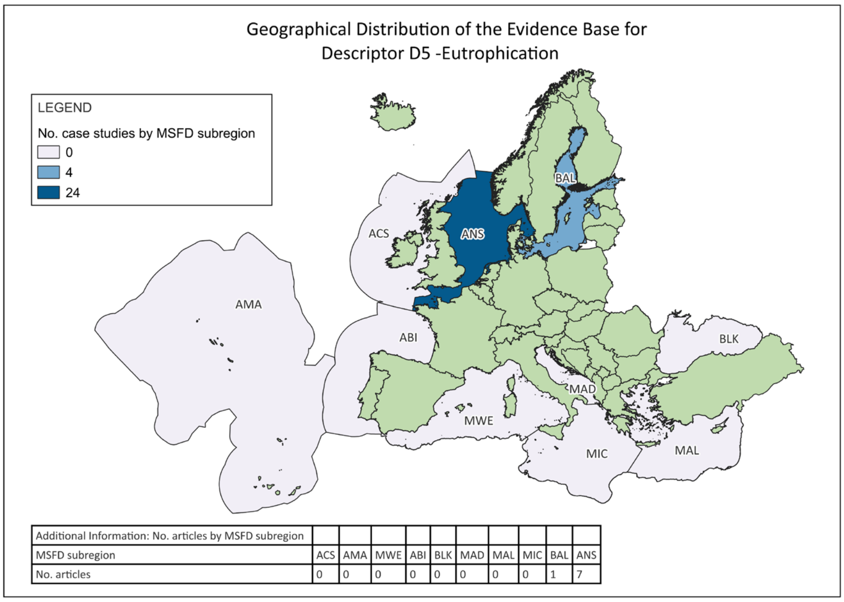


Figure 25. Distribution of bibliographic information for descriptor 5. Panel (a) shows the number of documents published per publication year (please note that 2024 (orange bar) is not a complete year: literature searches were undertaken in October). Panel (b) illustrates the distribution of the type of evidence. Lastly, panel (c) illustrates the number of articles per data collection period. Please note that in panel (c), "Reviews" (black bar) corresponds to Review type evidence (i.e., where data collection periods were not applicable); "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection period.

Geographical distribution of the evidence base

Geographic areas covered: 17% Baltic Sea and 83% northeast Atlantic Ocean (→ Figure 26)



Additional Information: No. articles by MSFD subregion										
MSFD subregion	ACS	AMA	MWE	ABI	BLK	MAD	MAL	MIC	BAL	ANS
No. articles	0	0	0	0	0	0	0	0	1	7

Figure 26. Number of case studies and number of articles by MSFD subregion for descriptor 5. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD)

Key findings

The impact of OWFs on nitrates and phosphates was varied. Enhanced phosphate and nitrate concentrations were observed in the surface layer of water (i.e., 5m depth) within the OWFs (Floeter et al., 2017). Specifically, phosphate concentrations in the surface water increased linearly with increased residence time of surface water within the OWFs (Floeter et al., 2017). Nitrate concentrations initially increased linearly with increased residence time within the OWFs, peaked after approximately 48 hours of residence time, and then started to decrease (Floeter et al., 2017).

Other criteria that were found to be impacted by OWFs include chlorophyll a (Chl-a), phytoplankton, primary production and light availability. Chl-a concentrations in the surface water were observed to increase linearly with increased residence time of surface water within the OWFs, with prominent pillars of high Chl-a concentrations observed in and around the OWFs (Floeter et al., 2017). It was estimated that changes in the spatial distribution patterns of Chl-a in the sea surface would follow the construction of OWF (Lu et al., 2022). Foundation installations are predicted to decrease phytoplankton abundance within 2 days of their installation in the vicinity of selected OWFs in regions categorised as non-problematic, potentially problematic and problematic eutrophication status. Turbine installations are predicted to increase phytoplankton abundance after 30 days only in regions with non-problematic eutrophication status (Kordan & Yakan, 2024). Predicted decrease (of up to 8%) in annual primary productivity predominantly within the vicinity and local to OWFs in the short term, with a larger regional effect that extends up to several 100s of km beyond the bounds of the OWF area in the southern North Sea area. These reported impacts vary spatially in the southern North Sea, with a predicted decrease in the centre of a large cluster of OWFs and areas with a predicted increase of up to 10% in net primary productivity (Daewel et al., 2022; Slavik et al., 2019). Improved light availability in the subsurface of the water column is predicted. In the empirical study, however, no difference in light availability was observed in three of four transects, both within and outside of OWFs, with a 20% reduction in 1% photosynthetically active radiation depth observed in the fourth transect (Daewel et al., 2022; Floeter et al., 2017).

With regards to the impact on macroalgae, macrofauna and Dissolved Oxygen (DO), a small positive impact on reef associated suspension feeders (bay mussels) was predicted, creating only 1 km^2 of new habitat, with negligible impact (<0.1%) on reef habitat areal coverage and seaweeds associated with reefs habitats- *Furcellaria sp* and *Fucus sp* in the Baltic Sea (Vaher et al., 2022). An increase in the overall abundance of blue mussels is predicted in the southern North Sea by more than 40% (Vaher et al., 2022). The aerial coverage of sandbank habitats increased by a minimal amount, with no significant impact on specific species associated with sandbank habitats, such as *Zostera sp.* and charophytes (stoneworts, clawed fork) (Vaher et al., 2022). Finally, the impact on DO concentration varied, ranging from predicted local reductions of approximately 0.3 mg L-1 on average and up to 0.68 mg L-1 in some areas, to less severe impacts in other areas, and an increase in concentrations in some areas (Daewel et al., 2022).

Cumulative effects

OWFs influence eutrophication by altering nutrient cycling, primary production and oxygen levels. Changes in hydrodynamics can either exacerbate or mitigate eutrophication, depending on regional conditions. Increased residence time within OWFs raises phosphate and nitrate concentrations, promoting phytoplankton growth and Harmful Algal Blooms (HABs). This can lead to organic matter deposition and localised oxygen depletion. Phytoplankton abundance in the vicinity of OWFs can vary immediately following foundation and turbine installations. OWFs also affect primary productivity and ecosystem structure by modifying light availability and chlorophyll concentrations. While some areas see improved photosynthesis, others experience reduced light penetration, affecting productivity. Predicted changes in net primary productivity vary regionally. Hard substrates introduced by OWFs support suspension feeders, such as blue mussels, potentially improving water quality through filtration. However, dissolved oxygen impacts vary, with some areas experiencing minor reductions.

Links to multiple pressures and state descriptors

There are potential links between D5 and D6 (Seafloor Integrity) primarily through the deposition of organic matter, which impacts benthic habitats. In addition, links between D5 and D7 (Hydrographical conditions) potentially exist as OWFs disrupt water circulation, affecting nutrient transport. Links also potentially exist between D5 and D1 (Biodiversity) and D4 (Food webs), given that changes in phytoplankton have the potential to alter food web structures. Given these complex interactions, further research is needed to assess OWF impacts on eutrophication.

Identified knowledge gaps

Despite growing research, significant knowledge gaps remain in understanding the long-term and large-scale impacts of OWFs on eutrophication. Uncertainties exist regarding the extent to which OWFs influence nutrient cycling across different marine environments and how these changes interact with broader climate-related shifts in ocean dynamics. Key gaps include limited empirical data on the cumulative effects of multiple OWFs within the same region. Uncertainty also exists in modelling the interplay between OWF-induced changes in hydrodynamics and nutrient distribution, with limited knowledge on the variability in regional responses to OWFs, requiring site-specific investigations to refine predictive models. In addition, there are insufficient studies on how OWF-associated habitats influence eutrophication processes over extended timescales. Addressing these gaps requires interdisciplinary research combining field measurements, long-term monitoring, and advanced modelling techniques to improve our understanding of OWF contributions to eutrophication.

Conclusion for Descriptor 5

OWFs impact eutrophication by modifying nutrient dynamics, phytoplankton growth, and oxygen levels, with varying effects across regions. Cumulatively, these changes interact with other pressures such as hydrographical alterations and biodiversity shifts, necessitating integrated environmental assessments. Significant knowledge gaps remain, particularly in understanding long-term and large-scale effects, highlighting the need for continued research and improved modelling to inform sustainable offshore wind development.

4.1.6 Descriptor 6. Seabed integrity

Authors: Andrea Cervantes, Maria Fernandes
Reviewer: Aurore Maureaud

Context

In regard to D6, the MSFD considers that a GES is achieved when "Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected" (EC, 2008). Following the European Commission's definition (EC, seafloor is: "a key compartment for marine life. It includes both the physical and chemical parameters of seabed (e.g., bathymetry, roughness (rugosity), substratum type, oxygen supply, etc.) as well as the biotic composition of the benthic community. Different kinds of habitats for sedentary and mobile marine species are formed inside and above the seabed." Moreover, integrity is inferred as: "comprehending both (i) natural spatial connectivity (avoiding unnatural habitat fragmentation or connectivity), and (ii) natural ecosystem processes functioning in their characteristic ways."

In accordance with Article 9(3) of the MSFD for the determination of GES, Commission Decision (EU) 2017/848 establishes criteria and methodological standards for Member States to assess the extent of achievement of GES for sea-floor integrity:

- **D6C1 – Primary:** spatial extent and distribution of physical loss (permanent change) of the natural seabed.
- **D6C2 – Primary:** spatial extent and distribution of physical disturbance pressures on the seabed.
- **D6C3 – Primary:** spatial extent of each habitat type which is adversely affected through change in its biotic and abiotic structure and its functions (e.g., through changes in species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), by physical disturbance. Member States shall establish threshold values for the adverse effects of physical disturbance through regional or subregional cooperation.
- **D6C4 – Primary:** the extent of loss of the habitat type, resulting from anthropogenic pressures, does not exceed a specified proportion of the natural extent of the habitat type in the assessment area.
- **D6C5 – Primary:** the extent of adverse effects from anthropogenic pressures on the condition of the habitat type, including alteration to its biotic and abiotic structure and its functions (e.g., its typical species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), does not exceed a specified proportion of the natural extent of the habitat type in the assessment area.

The purpose of the criteria for D6 is established as:

- **Criteria D6C1 and D6C2** are a means to assess the extent of physical loss and disturbance pressures on the seabed in general;
- **Criterion D6C3** is used to assess the extent of adverse effects from physical disturbance pressures per habitat type (criteria for other descriptors provide a similar function in relation to other specified pressures);
- **Criteria D6C4 and D6C5** are used to assess the extent to which GES has been achieved by considering all relevant pressures

More specifically, for D6, and as defined by the MSFD, physical loss refers to a permanent change to the seabed that has lasted or is expected to last for a period of two reporting cycles (12 years) or more. In contrast, physical disturbance is understood as a change to the seabed from which it can recover if the activity causing the disturbance pressure ceases.

Threshold values: to allow the assessment of the MSFD criteria, the threshold value concept was introduced under Commission Decision (EU) 2017/848, in accordance with Article 2(5). The use of the values, following Article 4 of the Decision, is to: "be part of the set of characteristics used by Member States in their determination of good environmental status". For seabed integrity, such threshold values are to be established either through the Common Implementation Strategy (CIS) framework (for D6C4 and D6C5) as recommendations to the Member States by the Marine Strategy Conservation Group (MSCG), or through regional and subregional cooperation (for D6C3) by referring to existing values under Regional Sea Conventions or the establishment of new values.

For criteria D6C4 and D6C5, threshold values were agreed upon in 2023. According to the Technical group on Seabed Habitats and Seafloor Integrity:

- The maximum proportion of a benthic broad habitat type in an assessment area that can be lost is 2% of its natural extent (≤ 2%) (**D6C4**).
- The maximum proportion of a benthic broad habitat type in an assessment area that can be adversely affected is 25% of its natural extent (≤ 25%). This includes the proportion of the benthic broad habitat type that has been lost (**D6C5**).
- A benthic broad habitat type is adversely affected in an assessment area if it shows an unacceptable deviation from the reference state in its biotic and abiotic structure and functions (e.g., typical species composition, relative abundance and size structure, sensitive species or species providing key functions, recoverability and functioning of habitats and ecosystem processes) (**D6C5**).

Impact of offshore wind energy expansion on seabed integrity

Literature searches and screening process

The diagram below (→ Figure 27) illustrates the process of identifying and screening the literature.

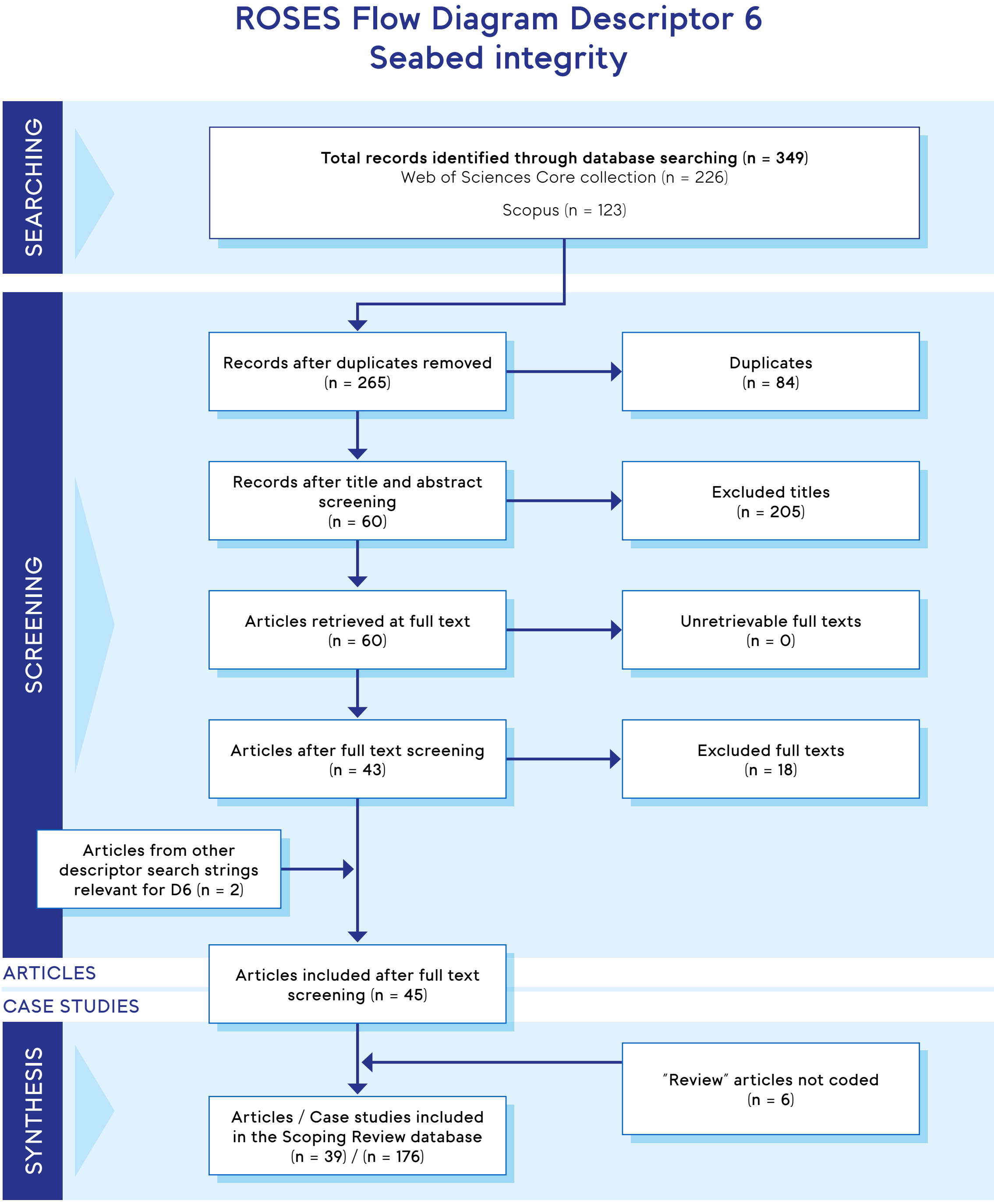


Figure 27. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D6.

Publication trends and data collection duration

Temporal coverage (→ Figure 28): The papers covered assessments from 1980 until 2021. Only one paper covered an assessment from 1980 to 2010 (Spielmann et al. 2023); the remainder spanned the period from 2001 to 2021.

Study type: 71% papers analysed reported empirical evidence, 20% reported findings from modelling, and 13% were reviews.

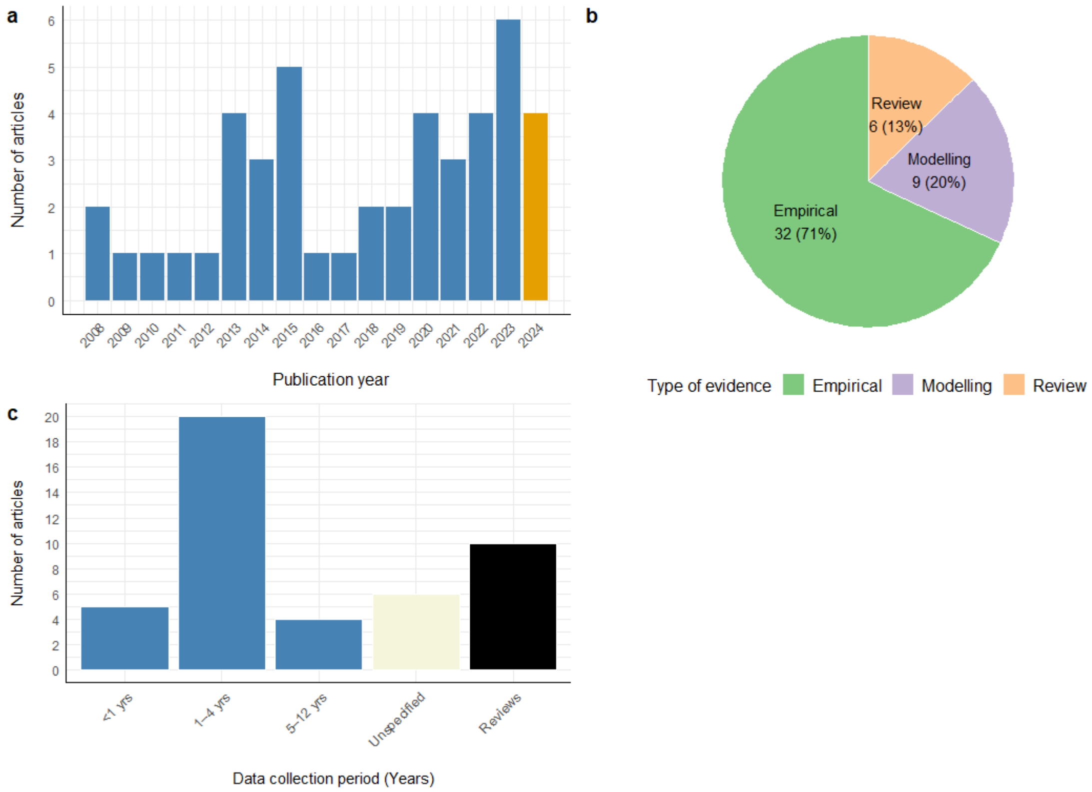


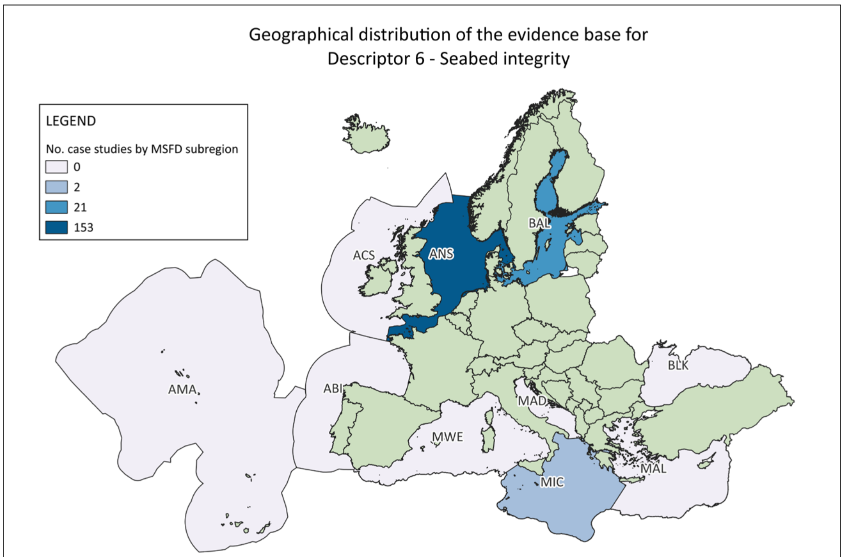
Figure 28. Distribution of bibliographic information for descriptor 6. Panel (a) shows the number of documents published per publication year (please note that 2024 (orange bar) is not a complete year: literature searches were undertaken in October). Panel (b) illustrates the distribution of the type of evidence. Note that counts are not mutually exclusive: 2 articles employed both empirical and modelling methods (Thus, panel b, n = 47). Lastly, panel (c) illustrates the number of articles per data collection period. Please note that in panel (c), "Reviews" (black bar) corresponds to Review type evidence (i.e., where data collection periods were not applicable); "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection period.

Taxa group assessed (seabed, fouling, pelagic and/or demersal): Several papers addressed more than one taxon group. Overall, 2% of the papers addressed algae, 9% of the papers addressed fish, 31 % of the papers addressed benthic fouling macrofauna, and 42 % of the papers addressed benthic seabed macrofauna.

Type of OWF foundations (monopile, jacket, GBFs, etc): 22% on GBFs, 22% included studies on Jacket foundations, 40% of the papers included studies on monopile foundations, six papers studied more than one type of foundation, and 12 were unspecified.

OWF life cycle stages studied (operational, installation, decommissioning): 1 paper on decommissioning, 4 papers on installation and baseline studies, six papers were unspecified regarding the stage studied. 69% of the papers focused on the operational phase of the OWF.

Geographic areas covered: 76% covered the Greater North Sea, 9% of the papers covered the Baltic Sea, and 2% of the papers covered the Mediterranean Sea (→ Figure 29).



No. articles by MSFD subregion										
MSFD Subregion	ACS	BAL	BLK	MAL	ABI	MIC	MWE	AMA	ANS	MAD
No. articles	0	4	0	0	0	1	0	0	34	0

Figure 29. Number of case studies and number of articles by MSFD subregion for descriptor 6. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD)

Key findings

Shifts in dominance and species composition (Bergman et al., 2015; Coates et al., 2015; Krone et al., 2013), sediment disturbance (Heinatz & Scheffold, 2023; Coates et al., 2015), areal loss (coverage) for macroalgae biotopes (mean effect size value <1) (Vaher et al., 2022), and colonisation of non-indigenous species and unwanted species are effects linked to OWF presence and life cycle activities. Jellyfish (*Cnidaria, Medusozoa*) and non-common native species in offshore areas without intertidal structures (J. W. P. Coolen et al., 2020; Vodopivec et al., 2017) are some examples mentioned where OWFs facilitated the dispersal of unwanted species. Increase of organic matter is also found as a result of bifouling with higher abundance of epibenthic macrofauna (Brandt at al., 2011; Nabe-Nielsen at al., 2014). Moreover, linkages are identified between suspended particulate matter (SPM) plumes and OWF turbines, where the origin of SPM plume material can be associated with biofouling. Scour protections on the seabed are suggested as the main cause of elevated SPM concentrations (Baeye & Fettweis, 2015).

A significant percentage of the reviewed research focused on the impacts on biofouling communities resulting from the presence of OWFs ("reef effect"). Reef effects from OWF presence showed a short-term contribution to habitat quality and an increase in biodiversity indicators (species richness, abundance, biomass and diversity). Moreover, scour protections of OWF foundations appear to be highly relevant for colonisation of epibenthic communities and for preserving macrofauna after the end of life of OWFs (Kingma et al., 2024; Spielmann et al., 2023). Nevertheless, observed effects vary across regions, seasons and OWFs (Gutow et al., 2014;. Ter Hofstede et al., 2022; Van Deurs et al., 2012; Vandendriessche et al., 2015) and long-term data analyses on effects of OWF installation (1980-2010) show relatively low diversity and abundance of macrofaunal communities (Coates et al., 2015).

Biofouling studies mostly focused on blue mussels (*Mytilus spp.*) and amphipods (*Jassa spp.*) as well as on depth (species distribution along depth gradients) (J. W. P. Coolen et al., 2022; (Gutow et al., 2014; Krone et al., 2013). Fouling activity, such as the production of faecal pellets by blue mussels and amphipods, has been projected to increase organic carbon deposition and mineralisation within OWF areas under current and future modelled scenarios in the North Sea (De Borger et al., 2021a; Mavraki et al., 2022). Conversely, however, surrounding OWF areas show a declining rate in both deposition and mineralisation processes, as well as carbon storage, indicating a spatial shift in benthic biogeochemical functioning due to the presence and future expansion of OWF developments (De Borger et al., 2021a).

Finally, management efforts (e.g., trawling bans) within OWFs appear to have significant effects on benthic ecosystems; however, these are only associated with longer-term measures and analyses. For studies on a short-term (up to 5 years) timeframe, no significant effects were found for soft substrate fauna (Vandendriessche et al., 2015), suggesting that no automatic restoration of the benthic ecosystem can be expected within a relatively short period of years (Bergman et al., 2015).

Cumulative effects

Cascading effects are linked to local increases in organic matter, productivity and further effects at higher trophic levels, including mobile demersal and pelagic megafauna (Gutow et al., 2014). However, altered carbon cycling effects outside OWFs can lead to transboundary shifts in benthic ecosystem functioning, potentially impacting neighbouring habitats beyond national jurisdictions. While immediate OWF areas may act as temporary carbon sinks on permeable sediments, activities such as construction, dredging, bottom trawling and decommissioning can lead to sediment disturbance and re-release of stored carbon (De Borger et al., 2021a).

The effect of bottom trawling bans (500 m) on the seabed after construction shows no spill-over effects on short-term studies, and no long-term effects (reversion of effects) if fisheries come back afterwards (Porz et al., 2024). There is a potential for recovery of abundance levels of macrofaunal species after installation activities. However, shifts in pre-impacted communities pose risks that can potentially affect species at higher trophic levels (Coates et al., 2015), which is particularly relevant for areas with less resilient macrofaunal communities under anthropogenic pressures.

Links to multiple pressures and MSFD descriptors:

- **D6 & D1 (Biodiversity):** Changes in species abundance, richness, community structure and diversity from benthic macrofauna (both seabed and biofouling communities) as well as demersal fish species.
- **D6 & D3 (Fisheries):** Assessment of bottom trawling bans and potential spill-over effects.
- **D6 & D4 (Food webs):** Changes in macrobenthic communities at a larger scale, shifts in species dominance and food web interaction
- **D6 & D5 (Eutrophication):** Organic matter deposition in benthic habitats and nutrient removal, mostly from reef effects, and contribution to the primary production deposited on sediments.
- **D6 & D7 (Hydrographical conditions):** Suspended particulate matter (SPM) concentrations, wake effects, turbidity and sedimentation

Identified knowledge gaps

For D6, most of the research has focused on analysing the impacts on benthic communities within a limited scope (local), i.e., at the OWFs site level, with 8 BACI studies out of 43. Regarding decommissioning, so far, there is limited experience with large-scale OWF projects and their effects on the marine environment. Moreover, standardised procedures and long-term surveys for monitoring programmes and dismantling remain to be developed (De Borger et al., 2021b; Spielmann et al., 2023). For SPM plume dynamics, considering the rapid expansion of OWFs, further studies on the wider-scale impacts of artificial hard substrates are needed (Baeye & Fettweis, 2015).

In general, most studies had a limited timeline. Long-term research is needed to cover the environmental impacts on seabed ecosystems from the different life stages of OWF developments. Moreover, cumulative effects related to different stages of OWFs on the sediment composition and macrofaunal community remain largely unknown. Overall, further research is needed to investigate the extent to which soft-bottom macrofaunal communities are impacted by the expansion of OWFs and decommissioning activities, as well as the long-term impacts of artificial reef effects for both soft-bottom and fouling communities.

Conclusion for Descriptor 6

Key findings indicate that OWFs' effects on macrobenthic communities result in colonisation (reef effects) and an increase in productivity, as well as local shifts in carbon cycling with contrary effects in surrounding OWF areas. Areal loss for macroalgae biotopes, physical disturbance, dominance shifts and colonisation of non-native species and/or unwanted native species are also impacts linked to OWF development. Cascading effects can occur for higher trophic levels, and indirect effects from management measures, such as bottom-trawling bans, remain inconclusive in short-term studies, while reference is made to the need for long-term monitoring. Knowledge gaps remain for long-term impacts and effects on the seabed beyond the local level, as well as for different life stages of OWF developments, including decommissioning.

4.1.7 Descriptor 7. Hydrographical conditions

Author: Javier Velázquez
Reviewer: Aurore Maureaud

Context

European marine environmental policy is largely shaped by the MSFD, which obliges member states (MSs) to achieve GES in their waters by 2030. Descriptor 7 (D7), which addresses alterations to hydrological conditions resulting from human activities, lies at the heart of this framework. Driven by global decarbonization targets, such as the Renewable Energy Directive (RED), offshore wind energy represents a crucial route to decarbonising and reducing greenhouse gas (GHG) emissions. However, the rapid development of OWFs introduces hydrographical stressors that put marine ecosystems at risk. The interaction of turbines, foundations, and cabling with dynamic coastal and offshore environments modifies sediment transport, wave energy distribution, and current regimes—mechanisms that support the health of benthic habitats, coastal resilience, and biogeochemical cycles.

This review assesses the hydrographical effects of OWF development in the context of the MSFD, relating these effects to overall ecological and regulatory targets. By synthesising evidence from 47 peer-reviewed studies (2011–2024) and finally selecting 39 peer-reviewed papers, it identifies the extent to which OWF infrastructure modifies D7's state indicators (e.g., flow velocity, wave climate) and proxies for cumulative pressures on nearby descriptors, e.g., biodiversity (D1) and seafloor integrity (D6). The results are then synthesised to derive actionable insights for the required expansion of renewable energy in line with GES achievement.

Impact of offshore wind energy expansion on hydrographical conditions

Literature searches and screening process

The diagram below (→ Figure 30) illustrates the process of identifying and screening the literature.

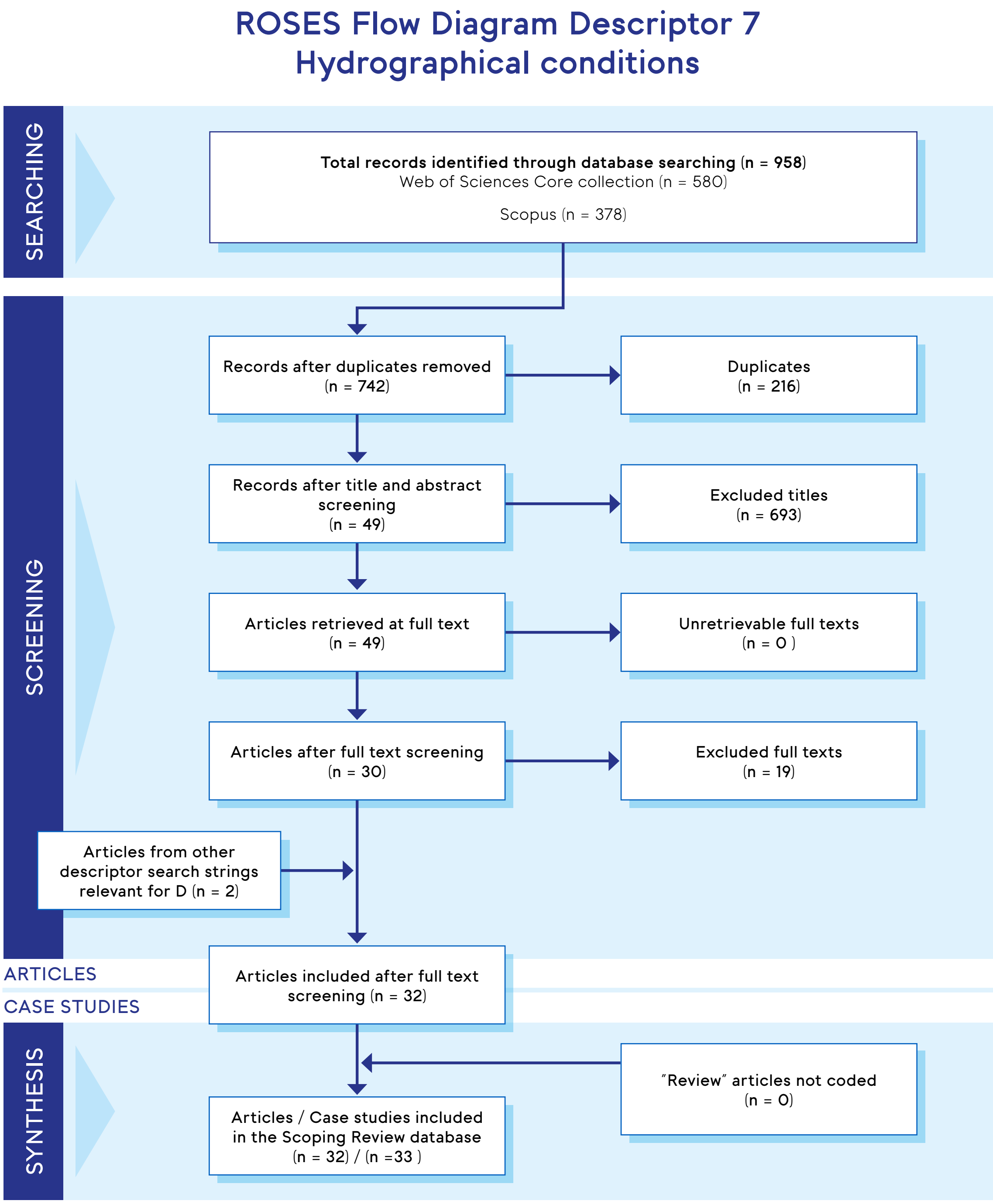


Figure 30. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D7.

Publication trends and data collection duration

Temporal coverage covered: 2008-2024.

Few articles were published in relation to D7 before 2014 (→ Figure 31). There has been a steady rise from 2015 onwards, with a maximum of 8 articles published in 2022. Concerning evidence type, 72% were empirical studies, while 28% were modelling. Concerning data collection periods, information was not commonly reported in retained articles.

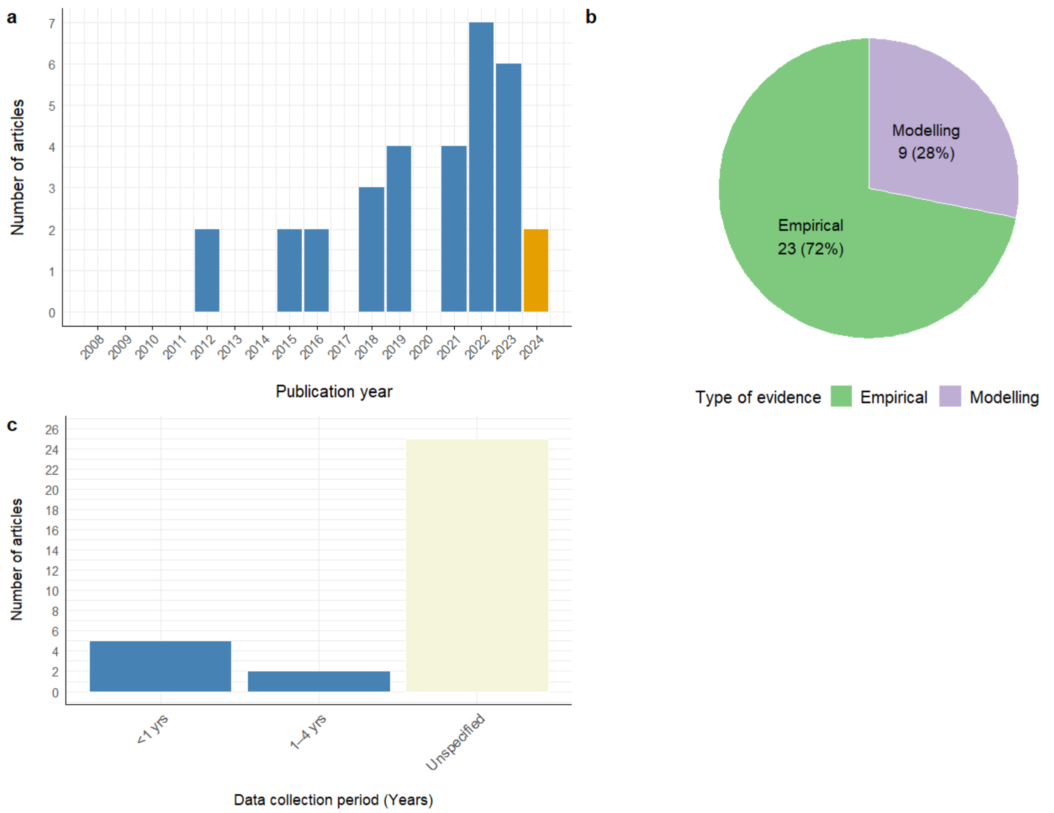


Figure 31. Distribution of bibliographic information for descriptor 7. Panel (a) shows the number of documents published per publication year. Note that 2024 (orange bar) is not a complete year, as literature searches were conducted in October. Panel (b) illustrates the distribution of the type of evidence. Panel (c) illustrates the number of articles per data collection period. Note that in the panel, "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection period.

Geographic areas covered

The majority (27 case studies) were situated in the Greater North Sea region (→ Figure 32), followed by the Baltic Sea, the Black Sea (two case studies), and the Mediterranean Sea.

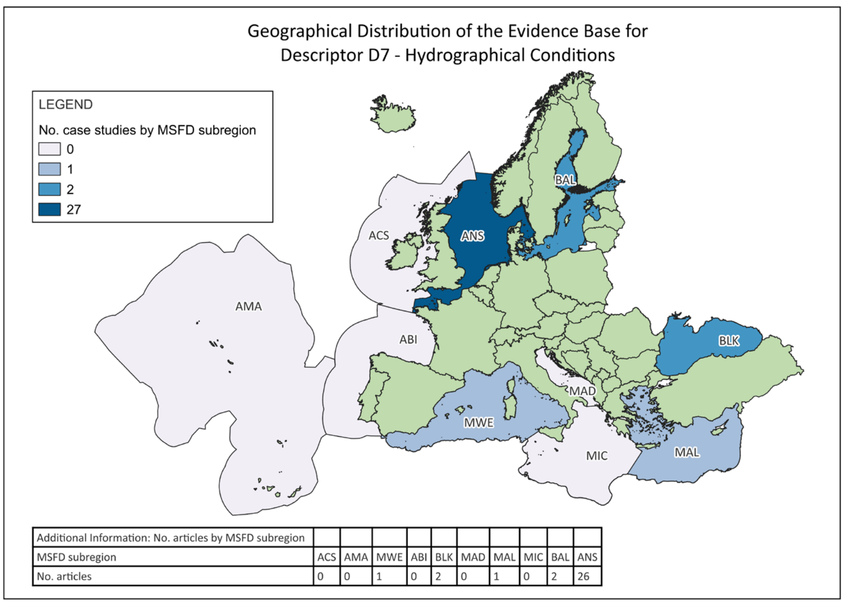


Figure 32. Number of case studies and number of articles in brackets [ ] by MSFD subregion for descriptor 7. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD)

The development of OWFs significantly alters marine hydrographical conditions (sediment dynamics, currents, wave energy, and density stratification in the water column) in a heterogeneous manner. The dominant OWF technology, monopile foundations, leads to an increased bed shear stress of 20–50%, destabilising sediments and forming a scour pit that reconfigures benthic habitats (Edesess et al., 2018; Rennau et al., 2012). Construction generates sediment plumes that increase turbidity by 15–30 NTU (Nephelometric Turbidity Units) and decrease radiant light penetration, thereby impairing primary productivity. For example, it results in a 10–25% increase in sediment accumulation in low-energy regions, such as the Baltic Sea, thereby burying seafloor ecosystems.

OWF arrays suppress downstream tidal currents by 5–15%, disrupting natural sediment transport and increasing the risk of erosion, and divert lateral flows by up to 10%, redistributing sediment patterns (Daewel et al., 2022). Wave heights are attenuated by 10–25% near turbines, leading to reduced coastal erosion in some regions and a deficit in sediment replenishment nearby. Wave refraction focuses on sensitive habitats such as salt marshes (Velarde et al., 2019). In stratified waters, turbulence generated by turbines can disrupt thermal stratification, decreasing vertical temperature gradients by 8–12% and altering nutrient cycling, which can lead to increased hypoxia (Carpenter et al., 2016; Christiansen et al., 2022).

In accordance with the MSFD, OWFs represent pressures that change hydrographical states and affect seafloor integrity (D6) and biodiversity (D1). Cross-descriptor interactions are driven by sediment plumes and by wave attenuation, making prior (integrated) management necessary. These interactions also highlight the need for balanced strategies to mitigate ecological risks while achieving renewable energy goals.

Cumulative effects

Cumulative impacts of OWFs expansion arise from spatial clustering (e.g., in high-density areas) and interactions with other anthropogenic pressures. In the North Sea, the world's most densely populated region for OWFs, where > 4000 turbines are scattered, large-scale arrays aggravate reductions of tidal flow and changes of sediment transport at the basin scale (Callies et al., 2019). Residual currents can be reduced by as much as 15% through the collective wake effects of several farms, thereby hindering natural sediment and contaminant dispersal (Daewel et al., 2022). These hydrodynamic shifts significantly increase dredging costs, undermine coastal protection measures, and disrupt the connectivity of organisms' habitats.

OWF effects are also synergistic with the pressure of fishing, shipping, and climate change. Seabed trawling disturbs sediment, thus increasing turbidity caused by OWF construction activities (Christiansen et al., 2022). Climate change increases coastal erosion due to sea level rise and stronger storms, a risk that is amplified when sea level rise impairs OWF-induced wave attenuation, thereby reducing sediment replenishment (Ghadirian et al., 2021). In addition, dredging for ship-related activities redistributes sediments previously destabilised by OWF-borne scour, further modifying the residence time and shape of the seafloor. Such feedback loops make ecosystem management more challenging, as sectoral pressures overlap in unpredictable ways.

These interactions highlight the important need for integrated marine spatial planning. The high-density OWFs have proven to be challenging, requiring adaptive strategies to mitigate tidal flow disturbances, sediment mismanagement, and cross-cutting pressures. By assessing sediment stability and developing dynamic zoning, proactive measures can be taken to minimise cumulative risks and resolve any necessary trade-offs between renewable energy and ecological resilience.

Identified knowledge gaps

There are still knowledge gaps regarding the impacts of OWFs. Most of the reviewed studies (66%) concern the North Sea region, while there are minimal studies in other European waters (only one Mediterranean study addresses near-field turbulence in Italy (Onea & Rusu, 2015). Monopile turbines are included in 80% of the studies using numerical models or measured in rather short time frames, severely limiting the validation of long-term effects (Van Berkel et al., 2020). Ecologically, few studies trace hydrographic changes through food webs, and while stratification perturbations may alter zooplankton distributions, their links to fish stocks remain unexplored (Christiansen et al., 2022). These interrelationships are essential for comprehensive ocean management.

Conclusion for Descriptor 7

Three main points emerge from this scientific summary: (1) OWFs have major impacts on hydrographic conditions, in particular sediment transport, currents and wave climate, with monopile foundations causing specific and permanent changes; (2) Tidal and sediment changes are exacerbated by cumulative impacts in high-density areas such as the North Sea, resulting in cross-descriptor effects on biodiversity (D1) and seabed integrity (D6); and (3) Major knowledge gaps - including long-term field studies, regional knowledge biases, and revolutionary linkages - impede full GES assessment. If policymakers are to balance renewable energy growth with marine conservation, they must adopt adaptive management frameworks — for example, through adaptive zoning and standardised sediment plume monitoring — while researchers should prioritize studies of diverse type of turbines and investigate understudied areas, such as Mediterranean and Black Sea waters, to ensure that solutions are relevant in all European waters.

4.1.8 Descriptor 8. Contaminants

Author: Margaret Kadiri
Reviewer: Javier Velázquez

Context

Assessment of Good Environmental Status: In relation to ‚Contaminants', the Marine Strategy Framework Directive considers that ‚good environmental status' is achieved when ‚Concentrations of contaminants are at levels not giving rise to pollution effects.'

Below is the list of the criteria and indicators for D8 assessment.

- **D8C1 – Primary:** Within coastal and territorial waters, the concentrations of contaminants do not exceed the following threshold values: (a) for contaminants set out under point 1(a) of criteria elements, the values set in accordance with the WFD; (b) when contaminants under point (a) are measured in a matrix for which no value is set under Directive 2000/60/EC, the concentration of those contaminants in that matrix established by Member States through regional or subregional cooperation; (c) for additional contaminants selected under point 1(b) of criteria elements, the concentrations for a specified matrix (water, sediment or biota) which may give rise to pollution effects. Member States shall establish these concentrations through regional or subregional cooperation, considering their application within and beyond coastal and territorial waters.

- Beyond territorial waters, the concentrations of contaminants do not exceed the following threshold values: (a) for contaminants selected under point 2(a) of criteria elements, the values as applicable within coastal and territorial waters; (b) for contaminants selected under point 2(b) of criteria elements, the concentrations for a specified matrix (water, sediment or biota) which may give rise to pollution effects. Member States shall establish these concentrations through regional or subregional cooperation.
- **D8C2 – Secondary:** The health of species and the condition of habitats (such as their species composition and relative abundance at locations of chronic pollution) are not adversely affected due to contaminants, including cumulative and synergistic effects. Member States shall establish those adverse effects and their threshold values through regional or subregional cooperation.
- **D8C3 – Primary:** The spatial extent and duration of significant acute pollution events are minimised.
- **D8C4 – Secondary** (to be used when a significant acute pollution event has occurred): The adverse effects of significant acute pollution events on the health of species and on the condition of habitats (such as their species composition and relative abundance) are minimised and, where possible, eliminated.

Impact of offshore wind energy expansion on contaminants

Literature searches and screening process

The diagram below (→ Figure 33) illustrates the literature identification and screening process. As shown in Figure 33, the literature search yielded 363 records, of which 261 were screened after duplicates were removed. At the title and abstract screening, 249 were excluded. Twelve were retrieved for screening, of which nine were excluded. After excluding review papers during the data extraction stage, two relevant papers were included.

ROSES Flow Diagram Descriptor 8 Contaminants

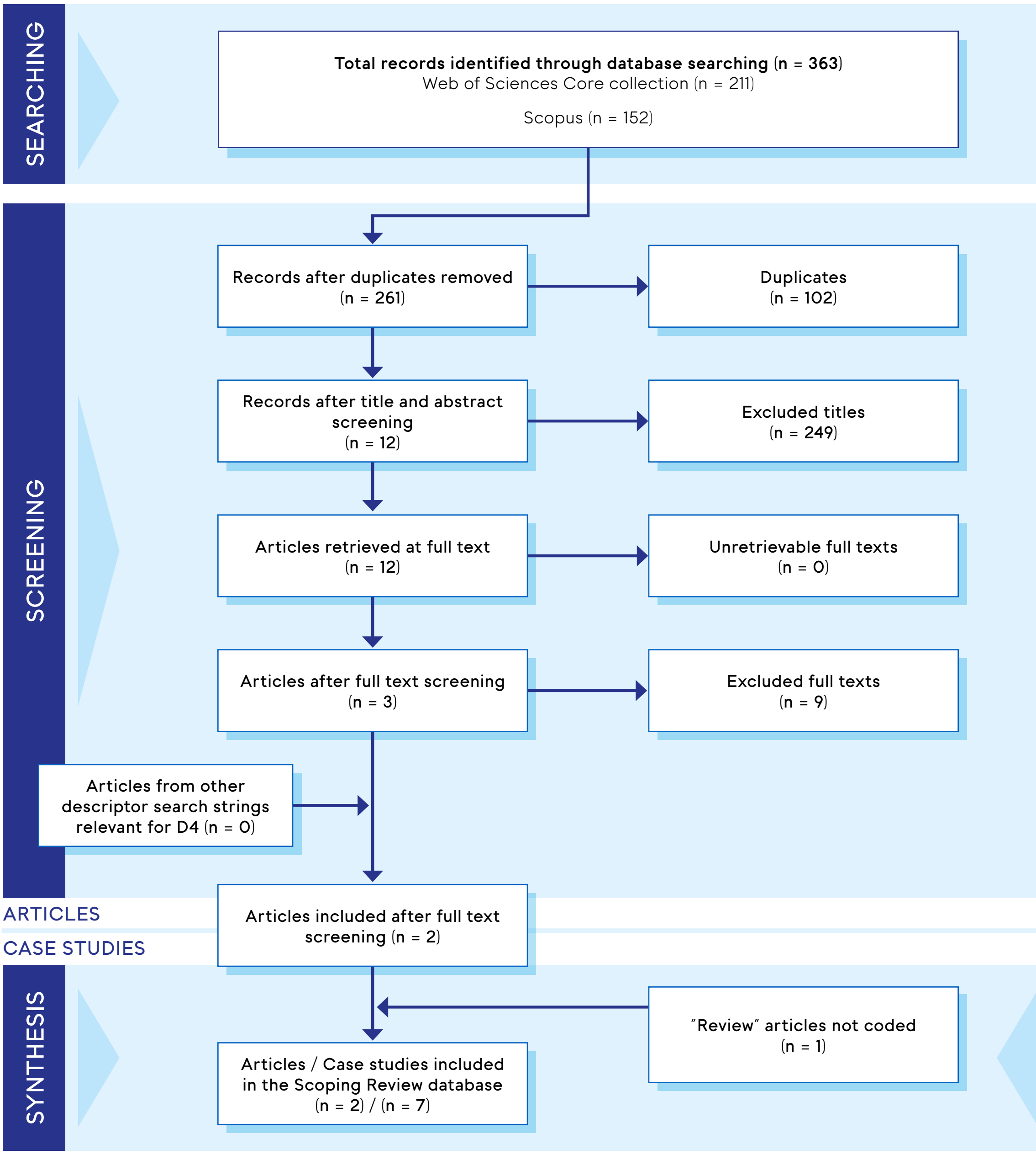


Figure 33. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D8.

Publication trends and data collection duration

Temporal coverage covered: 2014-2023 (→ Figure 34)

Study type (Empirical or predictive or review): 33% of the articles included empirical methods, 33% included predictive methods, and 33% were a review.

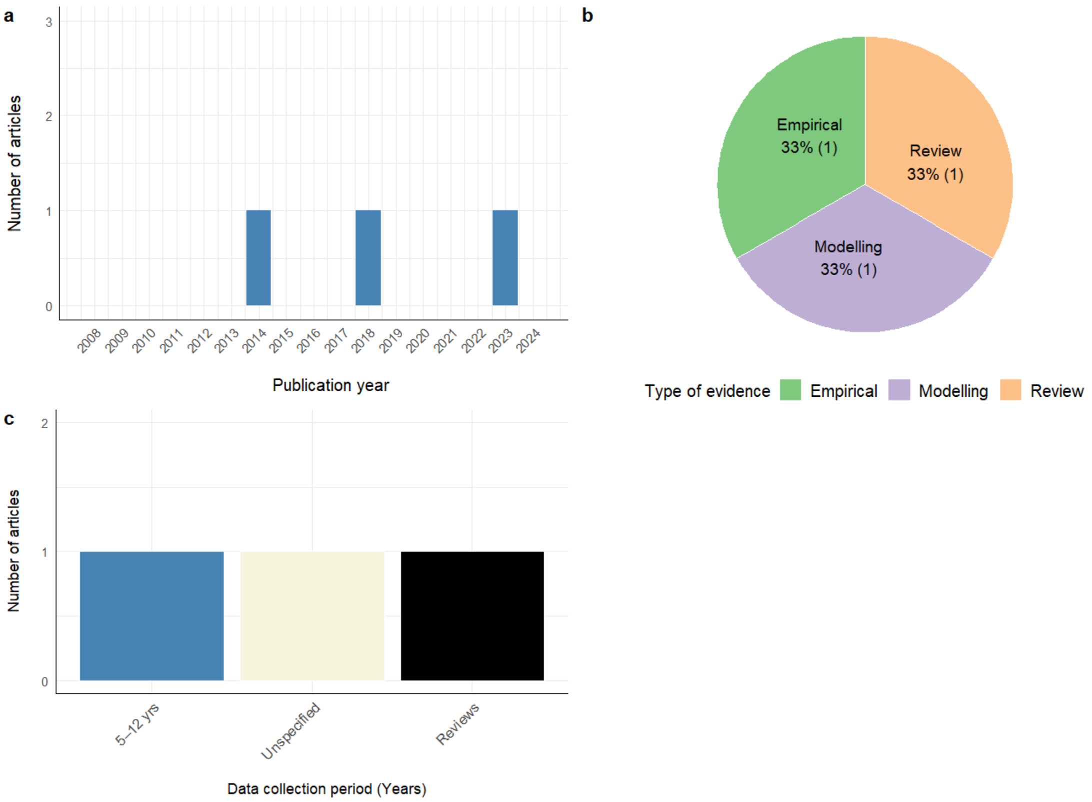
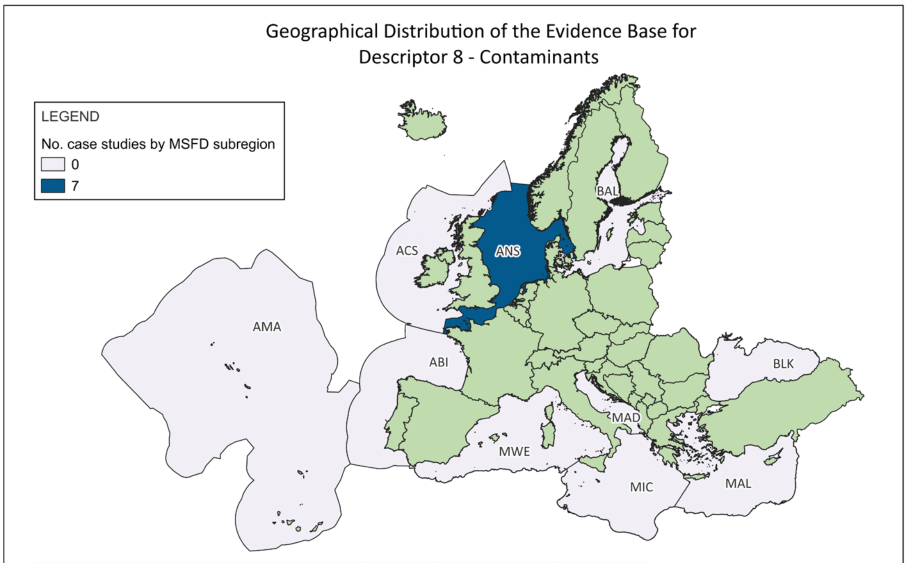


Figure 34. Distribution of bibliographic information for descriptor 8. Panel (a) shows the number of documents published per year of publication. Panel (b) illustrates the distribution of the type of evidence. Lastly, panel (c) illustrates the number of articles per data collection period. Please note that in panel (c), "Reviews" (black bar) corresponds to Review type evidence (i.e., where data collection periods were not applicable); "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection period.

Geographic areas covered

100% northeast Atlantic Ocean (→ Figure 35).



Additional Information: No. articles by MSFD subregion										
MSFD subregion	ACS	AMA	MWE	ABI	BLK	MAD	MAL	MIC	BAL	ANS
No. articles	0	0	0	0	0	0	0	0	0	2

Figure 35. Number of case studies and number of articles by MSFD subregion for descriptor 8. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western

Mediterranean Sea (MWE), and the Adriatic Sea (MAD)

Key findings

Impact of OWFs on metals

Variations were observed in the mass fractions of Cadmium (Cd), Lead (Pb), Zinc (Zn), Gallium (Ga), and Indium (In) in sediments, but they were all largely within the known range for North Sea sediments and do not give rise to pollution effects.

Cadmium (Cd) and Indium (In) were found to increase, with the increase significant for In. A decrease was observed for Lead (Pb), with no increase in Zn mass fraction and an increase and decrease in Gallium (Ga) depending on the site. However, Cd values were below the NOAA Effect Range Low (ERL) values, indicating that Cd had no significant impact on the marine environment. In contrast, Pb and Zn values exceeded the NOAA ERL values, suggesting a potential impact on the marine environment caused by Pb and Zn. NOAA ELR values indicate concentrations below which toxic effects on marine organisms are rarely observed. Indium mass fractions were found to be below the Predicted No Effect Concentration (PNEC).

Gallium and Indium are emerging contaminants added to galvanic anodes to protect OWTs from corrosion and biofouling by promoting the dissolution of the anode instead of the steel structure of OWTs. They are assumed to have a high affinity for adsorbing to sediments, and there are currently no known anthropogenic sources of these metals in the marine environment. However, there is no indication that the use of galvanic anodes in OWFs leads to the accumulation of Ga and In in sediment (Ebeling et al., 2023).

Cumulative effects

Pollution caused by contaminants can have deleterious effects, including harm to living resources and marine ecosystems, such as loss of biodiversity and hazards to human health. It can also hinder marine activities, including fishing, tourism, recreation, and other legitimate uses of the sea. Furthermore, pollution can impair the quality of seawater for use, leading to a reduction in amenities or, in general, the impairment of the sustainable use of marine goods and services. Such effects are likely to result from the direct or indirect introduction of contaminants into the marine environment, as a result of human activities, including the introduction of substances or energy (MSFD Art 3.8).

Links to multiple pressures and MSFD descriptors:

There are potential links between D8 and D1 (Marine biodiversity), as pollution due to contaminants released from sacrificial anodes in OWFs, for example, can have potential adverse effects that lead to loss of marine biodiversity. Similarly, there are potential links between D8 and D7 (Hydrographical conditions) as hydrodynamic processes, including resuspension of sediments during the installation and operation of OWFs and other more general processes, such as wind-induced waves, mixing and stratification, play a crucial role in influencing the concentration, distribution, and transport of contaminants including those released from OWFs. Additionally, there are potential links between D8 and D10, specifically microplastics from coatings, including paints, and paint abrasions from OWFs, which contain chemicals considered potential organic contaminants.

Identified knowledge gaps

There is extremely limited knowledge about the contaminant release from OWFs during construction, operation, and decommissioning, as well as their impacts on the marine environment.

Some key gaps include insufficient studies on the impact of the re-mobilisation of contaminated sediment due to seabed disturbance by cable and foundation construction. There is also a need for systematic studies to quantify and analyse the long-term release and ecological effects of contaminants from corrosion protection galvanic anodes (e.g., Gallium, Zinc, Indium and Aluminium) as well as the impressed current cathodic protection system. Current knowledge of the leaching behaviour of organic compounds (e.g., epoxy resins, polyurethane coatings) and their ecotoxicological impacts on the marine environment is insufficient. Similarly, limited scientific data exists on the environmental effects of corrosion protection systems used in OWFs (e.g., offshore wind turbines, offshore substations). There is a lack of comprehensive environmental monitoring strategies specifically focused on chemical emissions from OWFs, and analytical methods for detecting and quantifying contaminant release in seawater, sediment, and marine biota need further development and standardisation.

Conclusion for Descriptor 8

Given the extremely limited evidence of the impacts of OWFs on contaminants, it cannot be concluded with certainty that metals released from corrosion and biofouling protection measures are at levels which do not give rise to pollution effects. There are substantial knowledge gaps, including a lack of understanding of the long-term impacts and the effects of emerging contaminants.

4.1.9 Descriptor 9. Contaminants in seafood

Context

The Commission decision 2017/848 states that contaminants in seafood should not exceed levels specified in regulations. This is reflected the related criteria ↗ D9C1 which states that "The level of contaminants in edible tissues (muscle, liver, roe, flesh or other soft parts, as appropriate) of seafood (including fish, crustaceans, molluscs, echinoderms, seaweed and other marine plants) caught or harvested in the wild (excluding fin-fish from mariculture) does not exceed: (a) for contaminants listed in Regulation (EC) No 1881/2006, the maximum levels laid down in that Regulation, which are the threshold values for the purposes of this Decision; (b) for additional contaminants, not listed in Regulation (EC) No 1881/2006, threshold values, which Member States shall establish through regional or subregional cooperation."

Impact of offshore wind energy expansion on contaminants in seafood

Literature searches and screening process

No literature was found for this descriptor based on the scoping review process.

Conclusion for Descriptor 9

Our search criteria reveal a significant knowledge gap in the scientific peer-reviewed literature on this theme, which warrants more attention and represents a major focus, especially when OWFs may be considered as facilitating aquaculture (e.g., mussels).

4.1.10 Descriptor 10. Marine litter

Authors: Eirini Gallou, Bojana Ljubec
Reviewer: Jan-Claas Dajka

Context

In the context of MSFD, EU Member States are asked to achieve GES in their waters by 2030. Driven by global decarbonization targets, such as the Renewable Energy Directive (RED), off-shore wind energy represents a significant solution to achieving the reduction of global green-house gas emissions. This short scientific summary aims to describe the findings of the evidence review on the impact of offshore wind energy expansion on marine litter (D10). Marine litter is any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Under the descriptor, four subcategories exist to enable monitoring of GES:

- **D10C1 – Primary:** The composition, amount and spatial distribution of litter on the coastline, in the surface layer of the water column, and on the seabed are at levels that do not cause harm to the coastal and marine environment. Member States shall establish threshold values for these levels through cooperation at the Union level, considering regional or sub-regional specificities. Threshold values for macro litter (> 2.5 cm) on the coastline were published by the EU Commission in 2020, where Member States agreed to a threshold of 20 items per 100 m of coastline (van Loon et al., 2020). However, current discussions are ongoing to amend the proposal from the Technical group on Litter regarding the seafloor macro litter threshold value, aiming to improve the accuracy and relevance of the assessments for this criterion (including depth limit, monitoring area selection, and an adjustment of the numerical threshold value).
- **D10C2 – Primary:** The composition, amount and spatial distribution of micro-litter on the coastline, in the surface layer of the water column, and seabed sediment, are at levels that do not cause harm to the coastal and marine environment Member States shall establish threshold values for these levels through cooperation at Union level, considering regional or sub regional specificities.
- **D10C3 – Secondary:** The amount of litter and micro-litter ingested by marine animals is at a level that does not adversely affect the health of the species concerned. Member States shall establish threshold values for these levels through regional or subregional cooperation.
- **D10C4 – Secondary:** The number of individuals of each species which are adversely affected due to litter, such as by entanglement, other types of injury or mortality, or health effects. Member States shall establish threshold values for the adverse effects of litter through regional or subregional cooperation.

According to European MSFD the proposed thresholds (MSFD, 2008/56/EC; 2017/848/EU; Descriptor 10, criterion 2) identified for D10, suggest to monitor the composition and amount of litter (>2.5cm, D10C1) and microlitter (particles <5mm, D10C2) in various environmental matrices in order the assess the level of the pressure in the marine environment. D10C4 – is measured by the number of individuals of each species which are adversely affected due to litter, and D10C3 by the assurance that the amount of litter and micro-litter ingested by marine animals is at a level that does not adversely affect the health of the species concerned (thresholds for C4 and C3 are to be identified nationally). Due to this measurement approach, evidence for D10C3 could not be located as part of this review due to the focus on cause of impact and not simply measurable effects on marine life or specific species.

Impact of offshore wind energy expansion on marine litter

Literature searches and screening process

The diagram (→ Figure 36) illustrates the literature identification and screening process.

ROSES Flow Diagram Descriptor 10
Marine litter

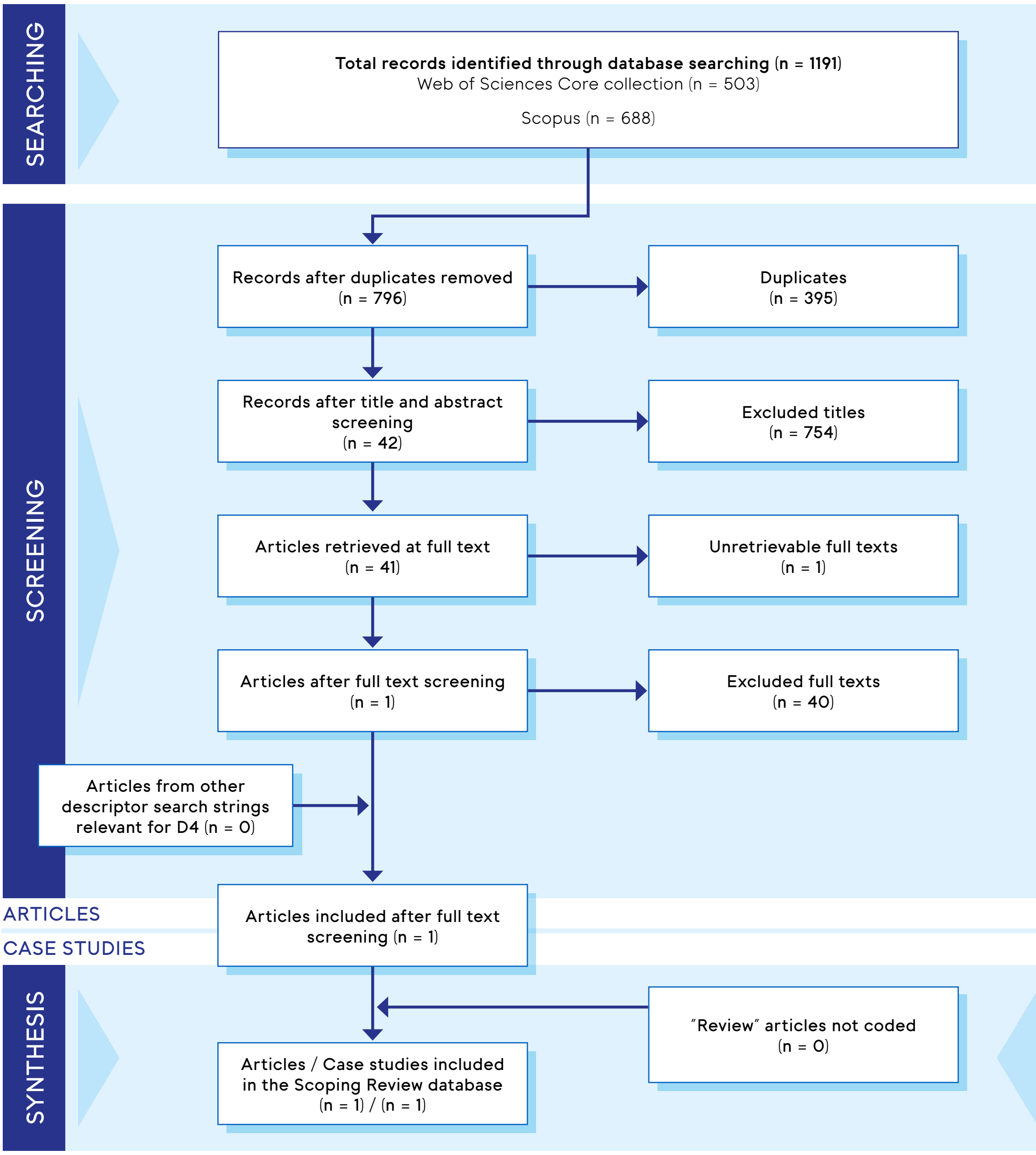


Figure 36. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D10

Key findings

The literature search returned 1191 papers, 754 of which were sorted out following screening due to their irrelevance to either the topic of marine litter or OWFs. Two were reviewed in detail and extracted to inform the SSS, as relevant to the role of OWFs in addressing marine litter. One of the papers did not provide evidence on the impact of OWF (instead proposing a methodological framework, which did not adhere to the selection criteria for retention). Therefore, only one paper was considered in this SSS, clearly showing that the evidence gathered through existing studies was very limited.

Geographic areas covered: Both studies retained referred to data from the North Sea.

Temporal coverage covered: 2023

The only relevant study on impact (Vanavermaete et al., 2023) suggests that marine litter in the OSPAR Greater North Sea region and the Celtic Seas is the impact of human activities (such as fisheries, sand extraction, wind farms and dredge disposal).

- **Data on litter distribution** in the main study retained, comes from a large-scale international beam trawl survey (BTS) and a local-scale environmental monitoring survey (EMS). The data collected was followed by polymer identification (FTIR spectroscopy) and statistical correlations to human activities.
- **OWF is not predominantly examined** as a cause for littering, as it is considered of limited interest for marine litter. Regarding the correlation between the presence of litter in and around OWF areas, there was no significant difference in litter observed between the impact, reference and nearby areas for OWFs.

Based on the limited evidence on the impact of OWTs that the review located, marine litter holds little relevance to the functioning of OWTs/OWFs. However, marine litter may increase due to materials deposited during construction, sand extraction, or relevant activities during the maintenance of OWTs (e.g., considering deposits at the seabed, both in the form of litter and micro-litter).

Cumulative effects

- **For seafloor litter,** fisheries-related items and plastic materials predominate in the literature as core causes
- **Hydrodynamic and geomorphological processes** can influence the spatial distribution of marine litter (Koutsodendris et al., 2008; Ramirez-Llodra et al., 2010), resulting in its accumulation in all habitats of the world's oceans.
- **The effects of dredge disposal** during maintenance and installation processes of OWFs cannot be unambiguously differentiated from the effects of hydrodynamic processes; thus, temporal studies during installation processes for OWTs may provide further evidence on potential cumulative effects.

Regarding the life cycle of OWFs, only decommissioning processes have been identified as contributing to marine litter in the literature; however, this will depend on the type of foundation and whether appropriate preventive measures are taken (Topham & McMillan, 2017). Further, Wang et al. 2018 showed that hydrodynamic changes due to OWF structures reduced micro-plastic abundance in the water and sediment in shallow sea areas (maximum 8m in depth).

Identified knowledge gaps

Only two studies relevant to marine litter were identified through the systematic review, and one was retained for its reference to the impact of OWFs, specifically studying the North Sea as a geographic area. The level of uncertainty is high in determining the role of OWFs in marine litter. Future studies that focus on littering during the construction or maintenance phase, but especially during decommissioning, would shed light on the type and amount of litter contamination created and deposited or transferred on the seabed/seafloor (as well as its expected dispersion)[5].

- **Abramic et al. (2022)** suggest considering further the decommissioning phase of OWT. At this phase, time-sensitive marine litter surveys and assessments, as well as surveys prior to construction and decommissioning, could shed light on current gaps.
- **Behaviour of offshore wind turbines** may differ based on various methods of construction and material choices in the construction specifications of the OWTs. This type of study is particularly important for areas neighbouring protected marine biodiversity areas or those coinciding with species migration routes.

5 Relevant recent activities by the scientific community are reflected in the setup of a sub-group on micro-particles from OWTs, by OSPAR ICG-ORED.

Currently, there is no evidence to inform the link between OWF and descriptors D10C3 and C4 based on the existing literature within the scope of our assessment.

- **Furthermore, it is important** to consider that fisheries and OWT may co-exist in certain locations, and the cumulative impact of these has not been studied in the studies examined.

Finally, regarding methodology of future studies, spatial sampling approaches need to be considered to capture the effects of remote accumulation, as the overall effect of marine litter on the marine ecosystem is hard to assess by only monitoring coastal and nearshore areas (Galgani et al., 2021), due to remote accumulation.

Conclusion for Descriptor 10

While evidence of OWT impact on marine litter is scarce, the effects of marine litter on biodiversity cannot be ignored, and further commissioned studies may shed light on the effects of decommissioning and installation (as well as OWT dredging-related activities). The cumulative effects of fisheries in OWT areas and OWTs' contribution to micro-plastics and micro-particles accumulation are also to be considered by future analysis on marine litter and the role of OWTs.

4.1.11 Descriptor 11. Energy, including underwater noise

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Context

Descriptor 11 of the MSFD covers the introduction of energy, including underwater sound, light, electromagnetic fields (EMF), heat and radiation. D11 monitoring and guidance have primarily focused on sound and EMF, so far. Unlike most pollutants, sound persists only as long as the source is active and dissipates completely when the source is inactivated. Two criteria for GES are identified in D11:

- **D11C1** - The spatial distribution, temporal extent, and levels of anthropogenic impulsive sound sources do not exceed levels that adversely affect populations of marine animals.
- **D11C2** - The spatial distribution, temporal extent and levels of anthropogenic continuous low-frequency sound do not exceed levels that adversely affect populations of marine animals. Reporting focuses on sound emissions at two one-third octave centre frequency bands (63 Hz and 125 Hz) representative of shipping.

For D11, the Technical Group on Underwater Noise (TGNoise) proposed implementation of the following threshold values that are based on the concept of Level of Onset of Biologically Adverse Effects (LOBE):

- **Impulsive sound sources:**
- **For short-term exposure** (one day, i.e., daily exposure), the maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than the LOBE, over one day, is 20 % or lower (≤ 20 %).

- **For long-term exposure** (one year), the average exposure is calculated. The maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than LOBE, over one year on average, is 10 % or lower (≤ 10 %).
- **Continuous sound sources:** 20 % of the target species habitat having noise levels above the Level of Onset of Biologically Adverse Effects (LOBE) cannot be exceeded in any month of the assessment year, in agreement with the conservation objective of 80 % of the carrying capacity/habitat size.

The purpose of the SSS is to describe current knowledge on how fixed-bottom foundations of OWFs may impact the achievement of GES in relation to D11. Four key phases during which D11 can be affected:

- **Baseline/ preliminary studies** - e.g., geophysics. During baseline surveys to determine site suitability and potential presence of unexploded ordnance (UXO), both types of sound sources are typically employed. Sources that are classified under D11C1 would be parametric sources and sparkers while the vessels carrying the sources are continuous (D11C2). UXO clearance which is carried out ahead of construction will also result in the generation of impulsive sound sources.
- **Construction** - during construction noise from continuous sources is always introduced by the vessels carrying out the operations (e.g., cable laying, foundation and turbine installation) and when certain technologies for foundation installation are employed, such as vibro-piling and vibro-jectting. Impulsive sound during construction is associated with pile-driving of the foundations.
- **Operation** - during the operational phase of a wind farm, continuous noise is introduced by the operational turbines and the servicing vessels that visit the site regularly. No impulsive sound sources associated with this phase have been reported, so far. In addition, electro-magnetic fields are generated by the cables carrying the electricity.
- **Decommissioning** - while decommissioning technologies are still under development with new tools coming on the market, it appears that techniques entail mainly cutting using a variety of tools (mechanical or using water jets), resulting in the generation of continuous sound in addition to the sound introduced by the vessels carrying out operations. Small order detonations are also a known way to cut "old" foundations; however, this does not appear to be a mainstream choice for decommissioning of wind farms.

Impact of offshore wind energy expansion on expansion energy & noise

Literature searches and screening process

The literature search returned 492 papers, 378 were scoped out following the abstract screening, 48 were reviewed in detail, and 30 were extracted to inform the SSS. The diagram below (→ Figure 37) illustrates the process of identifying and screening the literature.

ROSES Flow Diagram Descriptor 11
Energy and Underwater noise

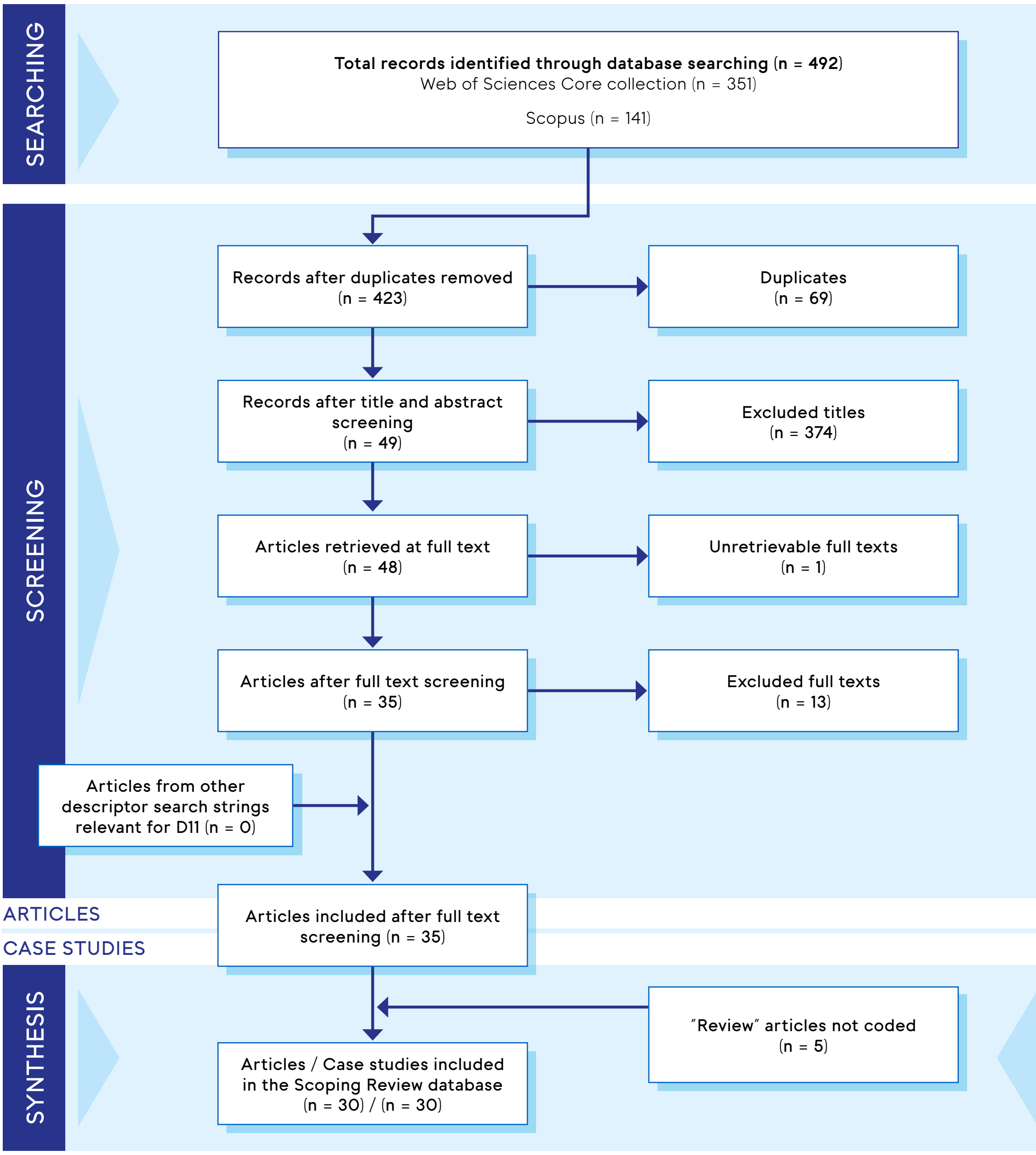


Figure 37. ROSES flow diagram illustrating the screening process and selection of literature for descriptor D11.

Publication trends and data collection duration

The literature reviewed encompassed studies published between 2008 and 2018; most of the literature (96%) consisted of peer-reviewed papers, while only one conference paper (3%) was included.

Most of the studies included in the extraction presented empirical evidence (60%), primarily from studies conducted in the North Sea or Baltic Sea, which, combined, represented 88% of the literature covered (→ Figure 38).

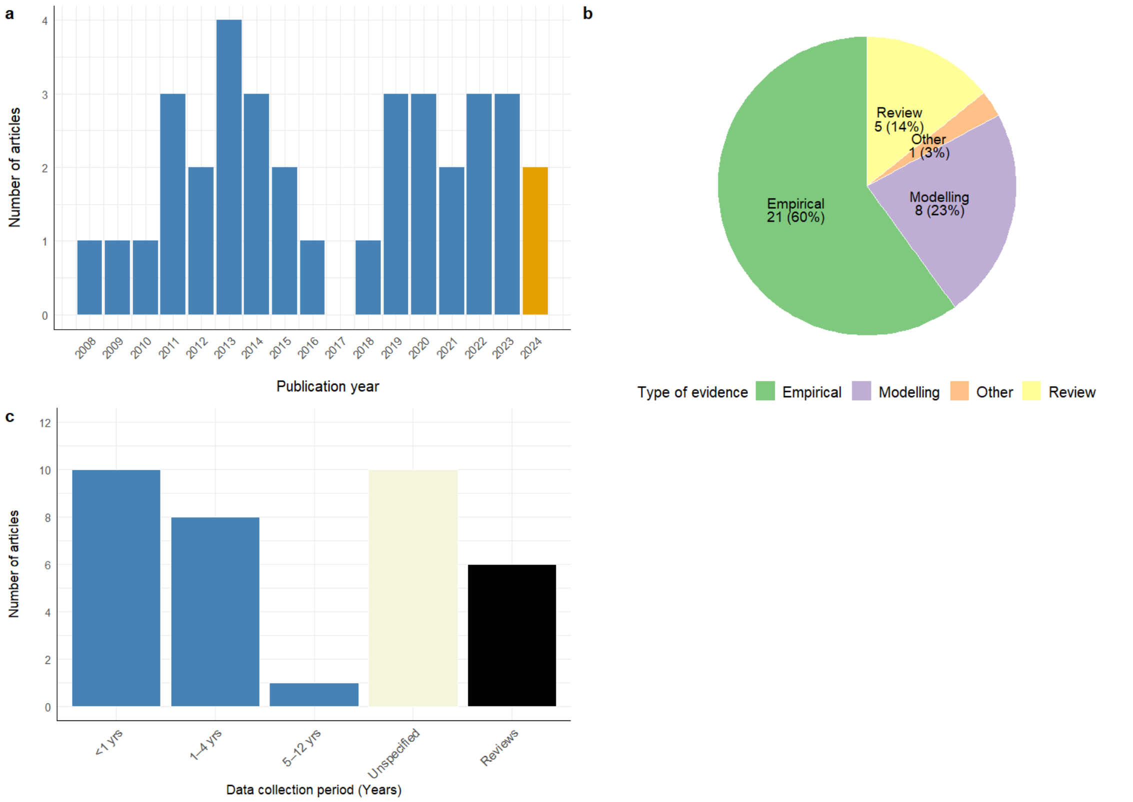


Figure 38. Distribution of bibliographic information for descriptor 11. Panel (a) shows the number of documents published per publication year (please note that 2024 (orange bar) is not a complete year: literature searches were undertaken in October). Panel (b) illustrates the distribution of the type of evidence. Lastly, panel (c) illustrates the number of articles per data collection period. Please note that in panel (c), "Reviews" (black bar) corresponds to Review type evidence (i.e., where data collection periods were not applicable); "Unspecified" (beige bar) corresponds to articles where authors did not specify the data collection period.

A few laboratory studies (8%) were also represented; these mainly referred to species relevant for the same seas. Such bias is linked to the fact that most wind farms installed to date are located in the northeast Atlantic and the Baltic Seas (→ Figure 39).

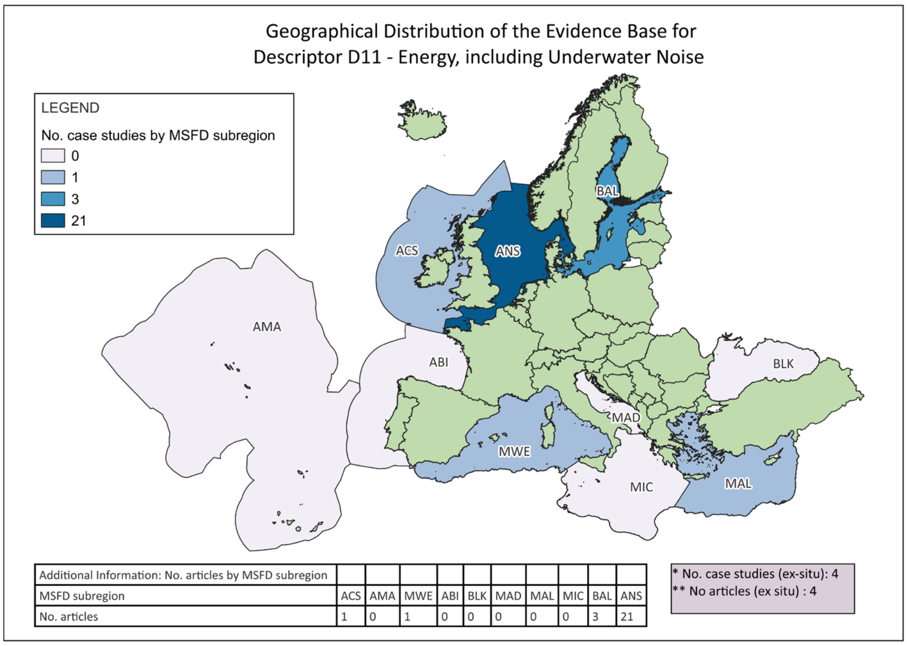


Figure 39. Number of case studies and number of articles by MSFD subregion for descriptor 11. MSFD subregions are the Greater North Sea including the Kattegat and the English Channel (ANS), the Celtic Seas (ACS), the Bay of Biscay and the Iberian Coast (ABI), Macaronesia (AMA), the Balkan (BLK), the Baltic Sea (BAL), the Aegean-Levantine Sea (MAL), the Ionian Sea and the Central Mediterranean Sea (MIC), the Western Mediterranean Sea (MWE), and the Adriatic Sea (MAD).

According to the scope of work, only fixed-bottom foundations were considered in the review, and the specific types are summarised in → Figure 40. The percentage of studies considering one or another type of foundation mirrors the spread that occurs at installed OWFs, considering that monopiles and jackets represent the vast majority of foundations currently supporting wind turbine generators offshore (→ Figure 40). Several studies analysed findings from multiple wind farms covering multiple types of foundations.

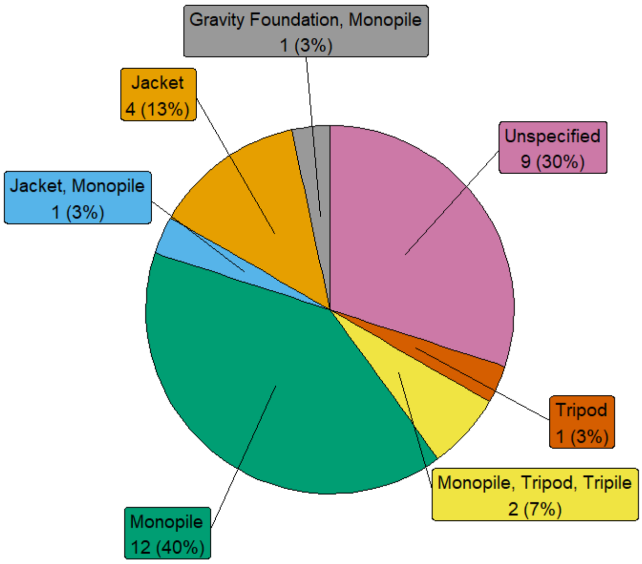


Figure 40. Number (and %) of different turbine foundation types reported in OWF noise impact studies. NB. "Unspecified" refers to unreported information. Multiple foundations are reported when a single studied OWF consists of multiple foundation types.

In the literature extracted, 20 studies reported on the installation (construction) of the foundations, while five reported on the operational wind farm. Only a few studies have presented results for more than one phase of a wind farm's lifecycle, e.g., construction and operation, or before and after construction, usually to draw comparisons on the potential impacts on the presence of marine mammals.

The majority of studies reported impacts on marine mammals (→ Figure 41), with all considering the harbour porpoise. Additionally, a few studies also examined effects on dolphins (n = 2) and seals (n = 1). No study reported potential impacts on baleen whales. Little literature was available on fish, and it was biased towards specific species, such as Atlantic Cod. Only one study reported potential impacts on tuna (for the Mediterranean).

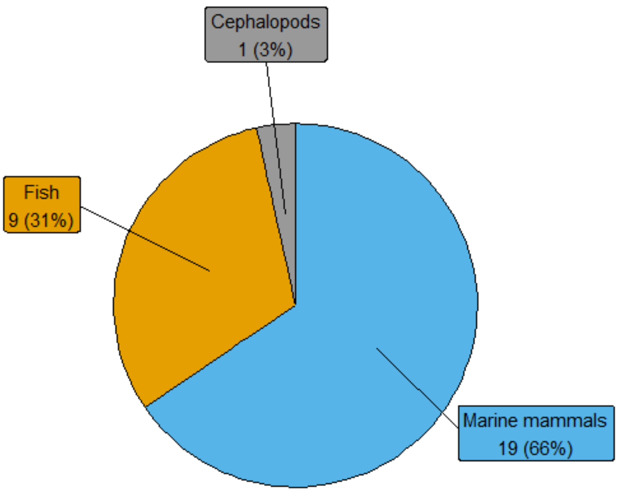


Figure 41. Number (and %) of studies reporting different taxa groups impacted by noise generated by OWF.

Key findings from the literature screened

The first criterion of D11 relates to the emission of impulsive noise. This criterion was the first to be addressed by EU member states in meeting the GES; therefore, national regulations to manage D11C1 are more mature and have led to a greater monitoring effort compared to D11C2, thus far. In the studies extracted, D11C1 was covered in most studies (n = 19), D11C2 in 4 studies, and both in only one study.

Impulsive noise is primarily generated during the construction of wind farms by means of pile driving. In many cases, sound levels during pile driving are reported, but not the effects on marine species. Therefore, the findings are of limited use unless further analysis is performed. Where impacts were assessed, given the geographic coverage of existing wind parks (northern Europe), studies have been focused on impacts on harbour porpoises, the main species of interest in the North and Baltic Seas. The impact of construction on harbour porpoise individuals has been documented in several studies, extending up to tens of kilometres (as measured by visual and/or acoustic studies) (Brandt et al., 2011, 2018; Schaffeld et al., 2020). On the other hand, population-level effects are yet to be determined and demonstrated. A framework for assessing population-level effects has been proposed, but data are necessary to build the knowledge base for the inputs (King et al., 2015; Nabe-Nielsen et al., 2014). .

Effects on porpoises included:

- **Avoidance** of the piling area for the pile-driving duration. Note that deterrent devices are often deployed as a mitigation measure; as such, avoidance may also be linked to the use of these devices.
- **Reduction** in acoustic activity of the animals; in other words, porpoises call less frequently
- **Potential** for injury and disturbance to marine mammals based on the recorded sound levels. Ranges of acoustic effects vary depending on the receptor species, the metrics applied for assessment, the implemented mitigation, and the particulars of piling (e.g., the energy applied). For example, a study noted that animals need to flee 2.4 km from piling sources to avoid injury (defined as TTS) (Schaffeld et al., 2020). The range is dependent on swim speed, reaction type, sound exposure level and propagation loss on site (site-specific).

Effects of fish included:

- **No mortality** found in common sole compared to control in a laboratory setting for sound exposure up to L_E of 206 dB re 1 μPa²s (100 strikes) (Bolle et al., 2012).
- **Area avoidance** when the SPL was above 120 dB re 1μPa during pile driving (modelled). Changes in swimming speed and behaviour in Atlantic cod, European perch, Atlantic salmon, and European plaice were reported (Rossington et al., 2013). However, field studies conducted in Belgian waters showed that cod presence was unaffected by piling at distances of 2-7 km, where sound pressure levels above Lp 120 dB re 1 μPa were experienced (Van Der Knaap et al., 2022).
- **Observed behavioural reaction** of cod to piling included high variation per individual with subtle effects on spatial behaviour. Observed animals moved closer to turbines during piling compared to before piling and even closer after piling, and changed depth slightly (no statistical significance compared to diel behaviour) (Van Der Knaap et al., 2022).

Construction also entails the use of vessels not only for the installation of foundations, which is often carried out by jackups (fixed above the waterline, therefore not introducing substantial underwater sound), but also to support vessels for cable laying and other operations. These contribute to D11C2 but have not been studied so far.

The second criterion relating to D11 relates to sound emissions from continuous sound sources. D11C2 has recently become a primary focus for national governments, and as a result, it is under-studied. The literature extracted showed that:

- **Marine mammals** affected by operational sound from wind farms were studied in only 2 of the retained literature: one modelling (Nabe-Nielsen et al., 2014) and one measurement study (Scheidat et al., 2011). Modelling predicted a 10.4% decrease in mean population size for the initial wind farms, followed by no further decrease for the inclusion of further planned wind farms (Nabe-Nielsen et al., 2014). On the other hand, a field study found twice as many acoustic detections during operation compared to baseline (Scheidat et al., 2011). Encounters were 72% longer, and the time between encounters was 39% shorter during operation compared to baseline. An increase in acoustic activity during operation was also confirmed compared to control sites (Scheidat et al., 2011). The increase in porpoise abundance in Dutch waters and within operational wind farms may be linked to increased food availability and a decrease in disturbance (e.g., fishing pressure). The modelling study (Nabe-Nielsen et al., 2014) also predicted a negative effect (however small) on distances of avoidance from small ships like those used for servicing wind farms.
- **Fish effects on the behaviour of cod** (both larvae and adults), including the orientation of larvae. No impact on swim speed nor turning behaviour, but larvae appear to swim towards the source (Cresci et al., 2023). Bluefin tuna exhibit a reaction to an increase in sound level by 25 dB compared to ambient levels at 20 Hz - 300 Hz, but not to the type of sound. Average depth and average tilt angle are also affected (statistical significance found) (Puig-Pons et al., 2021).
- **Only one study extracted on electromagnetic fields** found that static MF of 50-150 microT did not affect spatial preference and did not affect swimming behaviour of lesser sandeel larvae (Cresci et al., 2022).

Cumulative effects

Cumulative impacts of OWFs expansion arise from spatial clustering and interactions with other anthropogenic activities, such as fishing, shipping, and geophysical surveys.

While underwater sound is only present when a source is active, it can travel for hundreds (if not thousands) of kilometres, as demonstrated during the well-known Heard Island experiment (Munk et al., 1994). As such, species can be affected at large distances from the original source to different extents.

Moreover, OWF effects are synergistic with other pollutants, such as chemicals and contaminants, all of which contribute to a reduction in the survival of individuals and larger-scale populations.

Identified knowledge gaps

Several knowledge gaps remain in the collected evidence. These relate primarily to the area and species coverage. As previously mentioned, a significant bias exists in studies based on areas where wind farms have already been developed; therefore, the evidence gathered is of limited use for understanding potential impacts in under-explored geographical areas where different species are present. The majority of studies were conducted in the North Sea, followed by the Baltic Sea, where only a few marine mammal species are present and therefore studied. Evidence is lacking for baleen whales, sperm whales, dolphins, sea turtles, and any fish and invertebrates found in the Mediterranean or Black Seas. Given that large developments are anticipated in the coming years in southern Europe, where marine mammal species other than the harbour porpoise are present, a substantial knowledge gap needs to be addressed.

In some cases, where noise emissions generated from different activities are collected, results are only presented in the context of national guidelines (and/or regulations); comparatively, little additional effort would be required to calculate potential acoustic effects on other species.

Another limitation is that several of the scientific papers extracted ultimately referred to the same sites. In other words, multiple studies were undertaken at the same site, either looking at impacts on different taxa or at different stages of the wind farm lifecycle. Therefore, in effect, very little empirical evidence has been collected so far, and little effort has been put into collecting an extensive and comprehensive dataset. Baseline data is often too short to allow drawing significant conclusions on the impacts of wind farm installation on any species. In addition, the survey and decommissioning phases are often overlooked, likely due to the lack of regulatory requirements to monitor underwater noise during these phases.

Another limitation of the studies reviewed is that the use of acoustic deterrent devices (ADDs) is mandated in some countries as a mitigation measure; however, it complicates the interpretation of the effects because the purpose of deploying ADDs is to deter specific marine fauna from the area where loud noise will be generated.

Furthermore, descriptor criteria are assessed in isolation; however, there is overlap between the two, especially during the construction phase (e.g., piling plus vessel contribution) and the survey phase when a vessel is employed to deploy impulsive sources. There is a lack of methodology to assess the overall operation rather than individual parts.

Other large knowledge gaps are represented by the understanding of changes in particle motion associated with the various phases of a wind farm as opposed to sound pressure. The former is most relevant to understand and assess potential impacts on fish.

Moreover, even though electromagnetic fields and light are explicitly referred to in the description of D11, these pollutants are understudied. The keyword selection for the review may have contributed to the omission of relevant papers, as studies on electric fields or magnetic fields in isolation may have been overlooked.

Conclusion for Descriptor 11

High levels of impulsive noise (D11C1) are generated during the installation of wind parks; these have been shown to have the potential to injure and disturb marine mammals, as indicated by modelling studies and measured sound levels. However, observational studies have been conducted widely for harbour porpoises so far. Some behavioural impacts are reported for fish, such as changes in orientation and swimming depth. Evidence is too scarce to draw significant conclusions on this taxon.

Wind farms are also found to contribute to D11C2 during all life stages of an OWF. Few studies have addressed the potential impacts on marine biodiversity in this respect and have considered only the operational phase. Some knowledge about the potential impacts of D11C2 may be gathered from other sectors.

For both descriptors, further studies are needed that examine multiple species (and taxa) across long ranges to enable the quantification of acoustic effects during all stages of the project's life cycle. Furthermore, studies should always report unweighted sound levels so that weighting functions and criteria can be updated as new knowledge becomes available.

The effect of electromagnetic fields is understudied, despite being a pollutant that will persist over very long ranges for the entire operational life of the wind farm.

4.2 Workshop summary of findings

The results below integrate the Mural pre-workshop and workshop material for ease of presentation and coherence. The results are presented by cluster with a summary of the key findings for each (→ Annexe 7). The findings from the cluster-level discussions are followed by key takeaways from the plenary. Additional references suggested by cluster participants have been included in → Annexe 8.

4.2.1 Cluster 1: Descriptors D1 (Mammals and birds); D11 (Energy, including underwater noise)

The most significant knowledge gap identified in cluster 1 was the challenge of assessing cumulative effects, which are more commonly reported in grey literature (excluded from our SSS). These effects can vary significantly across short- and long-term time scales. Furthermore, there was a plea for better clarification over what cumulative effects or impacts involve, and to strengthen the study of temporal dimensions, such as through identifying research on "chronic effects".

Another key gap identified was the lack of standardised methodologies for assessing cumulative impacts, which hinders comparability across studies and limits the synthesis of findings. In addition, there are notable gaps in research on the potential impacts of decommissioning activities. The group highlighted a particular scarcity of observational studies on this stage, especially those that consider species-specific impacts and long-term displacement effects. Impacts may also differ depending on the chosen strategy, for instance, dismantling versus repowering. An important yet often overlooked phase is the exploration or pre-construction stage, which can have significant ecological impacts in itself.

Methodological challenges in impact assessment were also noted, and several suggestions were made to strengthen the final report. These included restructuring the species sensitivity score by taxonomic group to enhance clarity and better reflect species-specific responses, as well as explicitly clarifying early on that the focus is on fixed-bottom wind turbines. In the context of decommissioning, it was recommended that studies make a clearer distinction between different types of effects, such as noise generation, artificial reef creation, and marine fauna displacement, to improve understanding of the unique impacts associated with this phase.

4.2.2 Cluster 2: Descriptors D1 (Benthic habitats); D2 (Non-indigenous species:); D5 (Eutrophication); D6 (Seabed integrity)

In this cluster, participants discussed the core interdependencies between multiple descriptors in the scientific literature. In particular, they emphasised the need for a better understanding of the links between hydrological changes (D7), changes in organic matter, nutrients, and water transparency (D5), and their combined effects on biodiversity (D1) and seafloor integrity (D6). Cluster 2 participants highlighted several overarching knowledge gaps and issues.

An important knowledge gap discussed was the lack of attention to certain secondary effects, for example from "stepping stone" effects, which are not currently fully addressed by the EU MSFD. For instance, in relation to D1 (Marine biodiversity) and benthic species, it was observed that some native but potentially undesirable benthic species, such as certain crab populations, may benefit from scour protection measures and offshore installations, potentially leading to shifts in dominance and imbalanced ecosystem responses. Despite being overlooked, these effects may contribute to secondary dispersal processes that influence broader regional areas.

The introduction of hard structures and artificial reefs as part of OWF infrastructure was highlighted as contributing to permanent habitat change and, in some cases, should be considered a form of habitat loss rather than enhancement. Non-indigenous species also pose a significant concern regarding how OWFs may accelerate the spread of certain species at a regional scale, through both structural connectivity and associated activities, particularly during the construction and maintenance phases, which are often accompanied by increased shipping traffic.

The so-called "reef effect" was discussed in detail, with caution expressed against assuming these effects are inherently positive. While reef structures can enhance habitat complexity, they also create winners and losers among species and habitats, and may facilitate increased connectivity and the spread of species, including invasive ones, especially when coupled with shipping activities linked to OWFs. The classification of effects as "positive" or "negative" can further vary depending on the spatial and temporal scale, as well as on the specific descriptor being considered. For example, OWFs may be seen as causing habitat loss (a negative impact) under D6, while also promoting local aggregation of organisms around turbine bases (a potentially "positive" reef effect) under D1. Following this idea, participants also noted that oyster restoration efforts, while potentially beneficial, must be evaluated on a site-specific basis, as such interventions are not universally effective. Furthermore, the decommissioning phase of OWFs has been identified as a particularly understudied topic, including its impacts on artificial reefs. Participants also stressed the importance of scale in interpreting impacts.

Further gaps were noted concerning the impacts of pile driving and wake effects, particularly regarding sediment displacement and vibration impacts on seabed habitats, as well as the introduction of organic matter into the water column. This issue is closely tied to both eutrophication (D5) and hydrographical conditions (D7), with a lack of agreed-upon thresholds for acceptable levels of organic matter in offshore environments compounding the challenge. Additionally, changes in ecosystem services resulting from OWFs, such as carbon sequestration, were also noted as significantly understudied. Spillover and edge effects arising from the restriction of bottom-contacting gear fisheries require a wider and long-term analysis. However, new tools such as the ↗GES4SEAS toolbox are being developed to support assessments of complex interactions.

Several methodological challenges were discussed. For example, assessing the clustering of native species can be challenging, especially when considering cumulative or system-wide effects. Harmful impacts may be subtle or species-specific, yet lead to broader systemic or cascading effects. The identification of threshold values for ecological change was another key gap; such thresholds are difficult to extract from existing scientific literature, particularly at the level of individual descriptors.

4.2.3 Cluster 3: Descriptors D1 (Fish & cephalopods); D3 (Commercial fish and shellfish); D4 (Food webs); D7 (Hydrological conditions)

Participants discussed the core interdependencies between multiple descriptors and emphasised the need to better understand how hydrological conditions (D7) affect diverse types of fish and shellfish differently, with longer-term ecological consequences, as opposed to reporting the cumulative extent of harm in population sizes across multiple species.

In terms of the key overarching knowledge gaps and issues, one consideration was the limited knowledge available on the transboundary effects of OWFs. Experts suggested that the effects of upscaling the total OWF area should be considered in decision-making and impact assessments, as current studies are based on smaller-scale interventions and conclusions are often drawn accordingly. A significant aspect of the discussion was centred on the impacts arising during the operational phase of offshore wind farms, particularly in relation to marine mammals — an area noted as being underrepresented in research specific to this region. Furthermore, it was observed that the limited availability of spatial data, along with the absence of standardised indicators across studies, restricts the extent to which existing evidence can effectively inform policy. Many studies were found to focus on individual countries and relatively confined surface areas, limiting their broader applicability.

It was further observed that, although fisheries encompass a wide range of species interconnected through habitats, ecosystems, food webs (D4), and oceanographic dynamics (D7), assessments of cumulative effects from OWF often focus narrowly on changes in the abundance of individual species. The mechanisms by which these effects manifest over time, particularly in the context of fisheries management plans, remain insufficiently understood, highlighting the need for a more holistic, ecosystem-wide perspective that accounts for shifting ecological flows. Regulatory and management-focused studies were noted to be limited, with fisheries regulations and restrictions in and around OWFs varying considerably. Moreover, much of the necessary data is still forthcoming, and the implications for transboundary effects remain largely unclear.

A critical knowledge gap identified was in understanding how cumulative effects, such as disruptions in energy flow and nutrient transfer, propagate across trophic levels (D4), including producers, consumers, and decomposers, within an ecosystem. It was suggested that future research should prioritise the assessment of these interconnected dynamics to improve predictions of ecosystem responses to OWFs. At the same time, the need for longer spatiotemporal scales of mapping influence and impacts on food webs was emphasised due to the nature of the impact. The majority of existing studies were viewed as focusing on short- to mid-term effects (e.g., before vs. after construction of OWFs). Finally, although physical changes (e.g., altered water mixing, temperature shifts, nutrient redistribution) are addressed under other descriptors such as eutrophication (D5) and hydrographical conditions (D7), their implications for food web structure and function remain underexplored and should be considered and integrated into food web studies.

Several methodological suggestions and challenges were identified, including the need for evidence on OWF impacts to be derived from both predictive modelling and in situ observations. It was emphasised that these two data types should be clearly differentiated, with their respective strengths and limitations carefully considered. As previously noted, current assessments of food webs were regarded as lacking a holistic, ecosystem-wide approach and could be enhanced through the integration of network analysis. Additionally, the effects of the GES descriptors, indicators, and guidance framework on impact capture were also discussed, with it being suggested that many impacts across descriptors remain unaccounted for, as they are not always clearly specified within the framework or due to a lack of agreed thresholds in some cases.

4.2.4 Cluster 4: Descriptors D8 (Contaminants); D9 (Contaminants in seafood); D10 (Marine litter)

Participants in this cluster discussed the connections between the relevant descriptors, suggesting that these links primarily arise from the toxicity and bioavailability of contaminants to marine species, as well as the influence of tidal currents, sediment transport, and seabed bathymetry on the fate and movement of contaminants in the marine environment. Key links between marine litter (D10) and other descriptors, within contaminants in seafood (D9) and beyond this cluster, were discussed, including biodiversity (D1) and food webs (D4), with a particular focus on how contaminants and litter impact biodiversity and overall ecosystem health. Novel research linking types of litter, such as microplastics, with metals and other contaminants to health impacts (D9 and D10) and the consumption of seafood was discussed, with a focus on co-location for aquaculture sites. Connections to hydrographical conditions (D7) were also noted, due to the role of physical oceanographic processes in the transport of litter (D10), and their relevance for monitoring and assessment. These connections were considered potentially relevant to both synergistic and cumulative effects, especially those deemed 'second-order' and typically observable over extended timescales. Examples discussed included changes in prey availability or food web dynamics resulting from species ingesting marine litter associated with OWF, as well as potential human health risks from consuming fish contaminated with microplastics.

Several overarching knowledge gaps were highlighted, including the production and release of litter and contaminants, the methods by which existing studies assess marine litter and pollution, and the limited integration of non-academic literature (grey literature or reports) or a focused analysis of regulatory frameworks that fell outside the scope of this review. Future research could focus on the need to understand how tidal currents, sediment transport, and seabed bathymetry influence the fate and movement of contaminants in the marine environment.

Concerns were also raised about the absence of regulatory requirements for OWF developers to disclose the contaminants present in the materials they use. The current evidence gap was considered to be exacerbated by the lack of clarity regarding the likely sources of these contaminants, such as the submerged parts of turbine structures. Although materials can sometimes be identified through declarations provided by manufacturers, such information is not consistently available. In areas where OWF and fisheries coexist, such as the North Sea, contaminants, including microplastics and metals, may be found in seafood, prompting calls for targeted studies to assess associated health risks. A specific need for research linking microplastics, metals, and other contaminants to the contamination and consumption of seafood was discussed. The importance of such studies for demonstrating cumulative impacts and drawing connections between D9 and D10 was stressed, as was their significance for public health.

Additional gaps observed included the difficulty in assessing the effects of offshore wind energy (OWE) littering, largely due to challenges in directly attributing litter to turbines and in understanding how litter is transported across the sea and along the seabed. Furthermore, understanding the rate and extent of degradation of litter materials was identified as essential for determining high-risk types and tracing their effects on marine life, highlighting the need for long-term studies, particularly in multi-use areas where OWFs coexist with seafood production, such as in the case of blue mussels. Ongoing projects like ↗ OLAMUR were noted as important contributions to addressing gaps under D9.

Complementary research was recommended to assess the impacts of distinct littering processes (e.g., only microplastics accumulation, paints, or dredging) over different OWF lifecycle phases, including construction and decommissioning. The importance of spatial sampling was underscored, as both the location and timing of sampling were shown to significantly influence assessment outcomes and the ability to generalise findings across regions. For instance, conducting marine litter surveys prior to major OWF phases was seen as valuable in filling current knowledge gaps. To enhance monitoring and impact assessments, stronger collaboration across marine industries was suggested. Comparative studies involving the offshore oil and shipping sectors, both with a long-term presence in the North Sea, could provide valuable insights into the release and behaviour of contaminants over time. Lastly, while remote sensing technologies are increasingly being explored for OWF monitoring, questions remain about their ability to effectively detect and integrate contaminant data. It was recommended that any such systems be designed within a broader, integrated framework aligned with multiple MSFD descriptors to ensure a more holistic approach to environmental monitoring.

Several policy recommendations were made to address persistent evidence gaps related to OWFs and their environmental impacts. The strengthening of the regulatory and enforcement role of the MSFD was proposed, with particular emphasis on requiring suppliers and construction companies to disclose the materials used and their associated health and environmental risks. Additionally, improved transparency in material declarations would support more robust evidence gathering.

4.2.5 Plenary discussion and implications for policy

The goal of the plenary was to capture participants' immediate responses to the feedback from each cluster and to identify and discuss any cross-cutting issues/gaps. These outputs also helped shape the final format of the SSS.

The discussions within the clusters generated valuable insights that both supported the draft findings of the SSS report and highlighted key knowledge gaps. Suggestions included enhancing the visibility of interdependencies between descriptors, particularly in relation to the knowledge gaps. Furthermore, these discussions enabled expert recommendations for methodological improvements within the broader research landscape regarding the cumulative impacts of OWFs.

The plenary provided a platform to examine themes that emerged across all clusters, focusing on recurring challenges in methods, knowledge gaps, and how cumulative impacts are addressed in current studies. The key topics identified as especially relevant for informing evidence-based policy and promoting improved practices in the sector are summarised below:

Assessment, monitoring, management planning, and cumulative effects

A key challenge identified in the assessments was the aggregation of effects, both at the ecosystem level and for individual stressors, when addressing cumulative impacts. Significant uncertainties were noted even before such aggregation could be undertaken, emphasising the importance of regular and long-term monitoring to ensure adequate data generation. The need for monitoring to be more closely linked with strategic planning was highlighted, so that evidence could more effectively influence policy and decision-making processes.

Methodological recommendations across clusters included the development of comparative assessment frameworks for both monitoring and evaluating alternative renewable energy production methods. For example, lessons from the oil and gas industries could allow for a more holistic picture at the planning level decisions.

Recommendations also focused on improving quality assurance and environmental assessment processes within the procurement and commercial tendering system for OWFs, to enhance transparency in reporting and increase accountability for monitoring biodiversity impacts throughout the full life cycle. The role of industry and disclosures in effective monitoring, particularly when dealing with large numbers of potential contaminants, poses significant challenges. It is not easy or possible to track everything for potential harmful effects. It was suggested that a more effective approach would consider mandatory disclosures by industry, allowing for more targeted monitoring research that focuses on the most relevant effects. Furthermore, while the licensing processes (e.g., use of ratings) for OWFs are considered adequate, there is a need for specific indicators to translate robust research into effective management decisions and good practice. In this regard, it would be valuable to introduce mandatory indicators about management and governance. Aligning management practices with the guidance of OSPAR was considered a good way to ensure shared standards across all levels.

Use of toolboxes and models

While the scoping review and SSS identified multiple empirical studies, it was emphasised that the role of ongoing EU-funded projects and emerging assessment tools should also be considered. Examples of such tools, which have been built on previous work by ICES and Horizon Europe projects, were mentioned by participants. These included GES4Seas and the ↗ SCAIRM (Spatial Cumulative Assessment of Impact Risk for Management) model, which was developed to address spatial and cumulative challenges. Other tools from the work of research working groups such as ↗ OSPAR's Eco-C. and the ↗ GNSBI CIA-work track, were also cited. However, it was observed that the use of different tools across member states — often due to contextual or institutional preferences — hinders the comparability of the findings.

A more informed and consistent application of models was called for, including recognition of their limitations. Comparing model outputs to identify convergences and divergences was recommended, along with increased collaboration and information sharing among model developers. However, it was noted that such cooperation is rare.

Gaps in survey and decommissioning phases

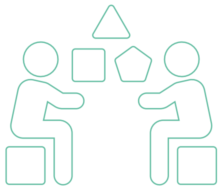
Significant research gaps were identified in relation to the decommissioning and survey phases of OWFs. It was also acknowledged that the survey phase, particularly high-resolution baseline surveys conducted prior to construction, has often been overlooked, despite its importance in enabling accurate and long-term environmental assessments. (e.g., cover depth, relief, sediment analysis, which are especially important for descriptors like D6 and D7). Moreover, as many installations are approaching the end of their operational life or undergoing modifications, strengthening the evidence base on decommissioning impacts was considered highly important[6]. This gap was observed across all SSS outputs and cluster discussions. Addressing these neglected phases was considered essential for enhancing the overall sustainability and effectiveness of OWF developments throughout their entire lifecycle.

There was also recognition that the survey phase was often neglected when assessing impacts.

6 The INSITE programme funded by UKRi is focusing on this process in the North Sea and generated some relevant evidence: ↗ www.ukri.org

5.

Discussion and Limitations



5.1 DISCUSSION AND LIMITATIONS

5.1 Cumulative impacts and effects

As OWF projects are expanding across European seas, studies on cumulative impacts and effects are expected to provide technical support for planning additional sites in a way that does not compromise biodiversity conservation. Cumulative effects can arise from multiple OWFs as well as other anthropogenic pressures, as described in the Introduction and the section "**Cumulative Impacts**".

Overall, assessing cumulative effects in this request is limited by two main factors, which were highlighted during the participatory workshop. Participants raised concerns about the lack of a standardised methodology in cumulative impact assessments, which complicated comparative assessments and synthesis efforts. Evaluating relevant spatial, temporal, and ecological (e.g., taxonomic) scales at which cumulative assessments could more efficiently highlight effects would facilitate study comparisons.

5.1.1 Cumulative effects from OWFs and other human activities

Most studies on the cumulative effects combining OWFs and other activities do not cover the full range of human impacts and usually focus on OWFs and one other human pressure or activity, while rarely considering the entire breadth of pressures.

Among the most common pressures, **fishing and OWF** effects have been investigated, especially the redistribution of marine mobile species resulting from the displacement of fishing pressure due to closed areas around OWFs and the concentration of commercial species through the reef effect (Raoux et al., 2017; Werner et al., 2024). There is a strong relationship between fisheries and OWFs due to the spatial redistribution of activities over time during the installation and operation phases of OWFs (Stelzenmüller et al., 2022). However, it is unclear from the literature whether OWFs and fishing pressure affect commercial species populations overall across their spatial range beyond local modifications of abundance. It is further unclear how cumulative effects are carried across species and species groups. When considered together with **climate change**, the redistribution of these commercial species can be amplified. The combination of **OWF construction and seabed trawling** is known to increase turbidity, which is a pressure already impacting many protected habitats across European seas (Bergman et al., 2015; Vandendriessche et al., 2015).

Other cumulative studies focused on the following themes:

- **OWF and climate change** are expected to amplify coastal erosion phenomena through wave attenuation and sea level rise, respectively.
- Eutrophication and changes in hydrodynamics, which are due to terrestrial **activities such as agriculture**, can either be mitigated or exacerbated by the presence of OWF in the environment. Since many species and habitats are sensitive to eutrophication, more knowledge on how OWF may affect eutrophication is necessary to ensure the achievement of GES
- **Maritime activities** (dredging and ship-related activities) around OWF sites can impact the seafloor further by modifying the shape of the sediments and their residence time

As reflected in the participatory workshop, the MSFD represents a good opportunity to identify key cumulative effect pathways from OWFs and other human activities through pressure descriptors. These were discussed in more detail during the clusters. An example of such pathways is that OWFs may release microplastics (D10) and metals in the water (D8). In areas where marine species are concentrated around OWFs, this can directly affect the GES of biodiversity groups, such as fish species (D1). Additionally, if fishing activities are ongoing around such OWF sites, OWFs can impact the quality of seafood and pose potential health risks (D9).

Evidence of cumulative effects due to OWFs and other human activities would be more insightful if it integrated most human pressures affecting the ecological compartment of interest. Fishing is the most represented human activity in combination with OWFs in cumulative assessments. More standardised methods would help to integrate findings across case studies. Current knowledge does not allow us to draw quantitative conclusions about the cumulative impacts of achieving Good Environmental Status with regard to specific criteria and descriptors. More formal cumulative effect pathways of OWFs through the MSFD descriptors can be one way to operationalise the impacts of OWFs for natural resource management and conservation.

5.1.2 Impacts arising from the development of more than one OWF

Without a doubt, impacts from multiple OWFs are expected to increase or amplify identified individual OWF impacts. According to the findings in this report, the nature of those cumulative effects is not always known, and they do not affect all descriptors of the MSFD. Quantifying whether OWF cumulative impacts are equal to, greater than, or smaller than the sum of individual impacts will be key to future maritime spatial planning.

Most evidence of impact from multiple OWFs comes from studies on **seabirds**, clearly showing that multiple OWFs can significantly **reduce the habitat areas** of species that tend to avoid OWF sites. Multiple species have been identified as avoiding OWF sites. The distance of avoidance has been quantified, showing that for those species, D1C5 on maintaining species habitat areas[7] is likely not going to be met in areas cumulating multiple OWFs (see, for instance (Garthe et al., 2023; Mendel et al., 2019; Peschko et al., 2024). The SR found evidence of such cases for species targeted by the Birds Directive and Natura 2000 sites (Mendel et al., 2019). When considering migratory species, only a portion of their habitat range is typically studied.

7 "The habitat for the species has the necessary extent and condition to support the different stages in the life history of the species." ↗mcc.jrc.ec.europa.eu

Multiple OWFs placed on species **migration routes** typically cause species to travel longer distances and modify their energy expenditures. However, exact estimations are generally unknown for individual species of interest. Although quantifying **mortality risks** around OWFs can be challenging, collision risks from the cumulative effect of OWFs are described in observational and modelling studies, especially in the North Sea.

The presence of more than 4000 turbines installed in the North Sea basin is known to cause **reductions in tidal flow** and **changes in sediment transport** (Callies et al., 2019). Currents can be reduced by 15% and alter the natural dispersal of sediments and contaminants (Daewel et al., 2022). Such a case illustrates how the cumulative effects of OWFs can cause impacts that accelerate with the expansion of OWFs, and subsequently affect ecosystems.

Beyond the North Sea, the transboundary nature of cumulative effects, especially on species and ecosystem processes, represents a research gap.

The cumulative effects of OWFs over space and time are better understood compared to the combined effects originating from a mixture of anthropogenic activities, likely because their impacts are similar and thus easier to evaluate collectively. Assessments of OWF cumulative impacts suggest that Good Environmental Status—particularly for descriptor 1 on biodiversity—may be at risk. However, for most MSFD descriptors, cumulative effects can sometimes be antagonistic or remain unclear, highlighting the need for further research as OWFs continue to expand throughout European seas.

5.1.3 Cascading effects that escalate within the ecosystem attributed to cumulative effects

From an ecosystem perspective, most evidence on cascading effects comes from the change in distribution of fish and invertebrates in relation to the artificial reef effect created by the OWFs. The structure of the ecosystem is altered by the introduction of hard-bottom fauna into soft-bottom areas, resulting in changed food web dynamics, increased species abundances, modified prey populations, and competition (De Troch et al., 2013; Halouani et al., 2020; Maar et al., 2009). This can further lead to trophic cascades and changes in energy flow. Changes in hydrographic conditions at the OWF sites cause an increase in organic matter and enhanced productivity, which are expected to affect higher trophic levels, such as mobile demersal and pelagic megafauna (Coates et al., 2014; Gutow et al., 2014; Porz et al., 2024). Modified ecosystem functioning from OWFs is relatively well understood on-site, but it remains unclear in larger areas or from a cumulative perspective at the ecosystem scale. Similarly, the duration of these changes is unknown, especially whether they will be sustained over long periods of time. For instance, it is unclear whether an increase in productivity and spill-over effects will remain long-term, and depend on the interplay with other human activities such as fisheries (also known to affect ecosystem productivity).

Cascading effects need to be quantified across space and time for European seas ecosystems. However, the duration of these effects is unknown. We recommend that OWF sites and their impacts be better investigated and integrated into quantitative and predictive studies to consider large-scale ecosystem changes. Additionally, more studies in less-represented areas should be conducted to test the generality of current findings in other areas.

5.2 Extracting knowledge gaps from the scoping review and participatory workshop

Despite the rapid expansion of OWF being seen as a key component to meet renewable energy commitments and achieving climate neutrality, significant knowledge gaps remain regarding the understanding of their cumulative and long-term environmental impacts. In the present study, one of the most persistent findings is the limited knowledge of the long-term and large-scale impacts associated with OWF development. Research suggests that many effects only emerge after extended timeframes, often beyond mandated monitoring periods, underscoring the need for longer-term studies.

From a geographical point of view, the reviewed literature is heavily skewed towards northern Europe, with literature sources covering 86% of the North-east Atlantic Ocean (primarily the Greater North Sea) and 12% of the Baltic Sea, while only 1.5% cover the Black Sea, and 0.5% cover the Mediterranean Sea (→ Table 4). Whilst a holistic overview of the descriptors is provided, formulating cumulative impacts per MSFD region proves challenging. For instance, little evidence exists on the impacts of OWF expansion in EU waters, such as the Black Sea, or any Mediterranean subsea region. Notably, only one study has covered the EU Outermost Regions and Overseas Countries and Territories, in Macaronesia (Elobei et al., 2022). This pattern of evidence most likely reflects the fact that northern countries (e.g., Germany, Netherlands, Sweden) are leading the way in terms of OWF installed capacity. This poses a knowledge gap. Henceforth, future research efforts and funding could be prioritised for less-studied regions such as the Mediterranean, where many OWFs are planned (cf. EMODnet Human Activities Wind Farms Map).

***Table 4**: Summary of the number of case studies per sea region, according to the Marine Strategy Framework Directive.*

MSFD MARINE REGIONS	NO. OF CASE STUDIES	SUBREGION	NO. OF CASE STUDIES
North-east	655	ANS - The Greater North Sea, including the Kattegat and the English Channel	630
		ACS - Celtic Seas	2
		ABI -The Bay of Biscay and the Iberian Coast	3
		AMA -Macaronesia	1
Mediterranean Sea	12	MWE -Western Mediterranean Sea	5
		MAD - The Adriatic Sea	2
		MIC - The Ionian Sea and the Central Mediterranean Sea	3
		MAL -The Aegean-Levantine Sea	1
Baltic Sea	75	BAL - Baltic Sea	65
Black Sea	6	BLK- Black Sea	5
NA	4	Ex-situ	4

Another important gap lies in the life cycle coverage of OWF studies summarised in the SR. While a significant amount of research is focused on operational and construction activities, other life cycle stages, such as pre-construction and decommissioning, remain largely unexplored across MSFD descriptors. This is also in line with the workshop summary of findings, as currently, there are very few examples of decommissioned OWFs in EU waters.

In addition, a disconnection appears to exist between OWF studies and the criteria defined under the MSFD, as well as the descriptors for assessing GES. While many studies address relevant ecological data and impacts on marine ecosystems, few of them seem to recognise, or assess, the linkage with GES and, for example set threshold values on certain environmental pressures. This represents a clear gap between EU-focused research and policy, which could be an area of opportunity to support monitoring and reporting within MSFD processes.

To address knowledge gaps identified in the scoping review and participatory workshop, the following critical areas require urgent attention:

Species and taxonomic coverage

- **Bats:** Increasing evidence shows that OWFs impact bat migration routes and pose collision risks, yet population-level consequences remain poorly understood.
- **Marine mammals:** Studies disproportionately focus on harbour porpoises (*Phocoena phocoena*), with minimal data on other species like dolphins and seals. Acoustic impacts on cetaceans, beyond behavioural changes (e.g., reproductive success, long-term displacement), are under-researched.
- **Reptiles:** No studies have addresses marine turtles at all, despite their vulnerability to habitat fragmentation and electromagnetic fields from subsea cables. This may reflect the fact that few impact studies were retrieved in the Mediterranean subregions despite the presence of six turtle species across Mediterranean waters (especially the Loggerhead, Green and Leatherback, which are found throughout the Central Mediterranean, Aegean and Levantine Seas)

Descriptor-specific shortfalls

While the knowledge gaps per descriptor are listed in the SSS, here are a few crosscutting shortfalls:

- **D2:** geographic coverage and literature availability are extremely limited.
- **D3:** The literature review remains uncertain about whether offshore wind farms ultimately benefit or disrupt fish populations. Especially, results of modelling studies assessing fish stocks should be treated with caution, as they are prone to bias and reporting of overestimated fish stock sizes and resulting catchment rates (Graham et al. 2024), leaving depleted stocks. Further, the interaction of OWFs with overfishing remains poorly understood, particularly how displaced fishing effort may intensify pressure elsewhere (Gill et al. 2020). Especially given that major fishing grounds, such as the German whitefish fisheries in the North Sea, are located in areas designated to OWF development (WWF 2025), and that bottom trawling activities do not necessary respect MPA boundaries (WWF, 2025), there is a need for a better understanding of economic and societal impacts of OWFs and the ecosystem services that support fisheries.
- **D4:** While "artificial reefs" (colonisation from the presence of structure such as scour protection) may increase local biomass, long-term trophic cascades and cross-regional spillover effects remain unstudied.
- **D8:** Limited evidence exists on chemical leaching from turbine materials (e.g., anti-corrosive coatings, galvanic anodes) and microplastic shedding from cables. Only two studies measured metal concentrations near OWFs, finding levels below PNEC thresholds.
- **D9:** No paper was found for evidence of contaminants in seafood in relation to OWFs, while OWFs' artificial reefs have been considered to potentially facilitate aquaculture (oyster, mussels, etc.). If the co-location between fisheries and offshore wind farms continues, research funding should be allocated accordingly.
- **D10:** Decommissioning-related debris and its hydrodynamic dispersal patterns are poorly studied.
- **D11:** pressures other than underwater noise and life cycles other than construction of a wind farm are under studied.

Methodological and policy linkages

- **MSFD criteria alignment:** Few studies explicitly reference GES thresholds (e.g., D6C4's 2% habitat loss limit), hindering policy integration.
- **Cumulative impact assessment:** Standardised frameworks for evaluating spatially/temporally overlapping pressures (e.g., OWFs + fisheries + shipping) are lacking. Workshop participants emphasised the need for ecosystem-level modelling that also accounts for climate-driven shifts in species distributions.

Life cycle and geographical imbalance

- **Pre-construction stage:** Assessment of effects from pre-construction activities, such as exploration, site characterisation and feasibility studies, is generally overlooked for OWF development, with potential impacts on various MSFD descriptors. Further prioritising Before-After (BA), and Before-After-Control-Impact (BACI) study designs would be beneficial.
- **Decommissioning:** There is limited knowledge regarding decommissioning activities in OWF projects and their impacts on the marine environment. Standardised procedures and long-term surveys for monitoring programmes and dismantling also remain to be developed.
- **Regional disparities:** 86% of studies focused on the North Sea, while the Mediterranean and Black Sea regions, with planned OWF projects, had ≤5 studies each (→ Table 4). Macaronesia is virtually unstudied despite its unique biodiversity risks.

Socio-economic and climate interactions/trade-offs

- **Climate interactions:** No studies modelled how OWF-induced hydrographic changes (e.g., altered currents) might amplify warming or acidification impacts.
- **Socioeconomic dimensions:** While 39 of the studies pertaining to D3 addressed fisheries displacement, none quantified trade-offs between renewable energy targets and small-scale fishing livelihoods.

Workshop-driven recommendations

- **Develop EU-wide protocols** for assessing transboundary impacts (e.g., noise propagation across EEZs).
- **Prioritise before-after control-impact (BACI) studies** spanning ≥10 years to capture adaptive responses.
- **Integrate autonomous sensors and eDNA metabarcoding** into OWF monitoring to resolve biodiversity changes at scale.

> Addressing these gaps will require coordinated efforts across policymakers, researchers, and industry alike to align the impacts of OWF expansion with the MSFD's precautionary principles.

5.3 Limitations

The limitations of the methods are outlined separately (below) for the scoping review and the participatory workshop. However, it is important first to acknowledge the overarching limitations that affected both components. Firstly, the short timeframe required the development of a specific methodological framework, focusing on academic literature and a single workshop event. Indeed, grey literature was excluded, therefore limiting the summarised knowledge to peer-reviewed literature only. This may be an important drawback as experts from the participatory workshop identified that cumulative effects may be more commonly reported in the grey literature. However, the combination of the scoping review and participatory workshop offered some degree of external validation for the review and, importantly, added greater value to the overall findings, even if our approach was not as comprehensive as a full systematic map/review. Additionally, the scope of the work was shaped by the specific focus on the MSFD, with a clear geographic focus on Europe, as defined by the requester and the directive.

5.3.1 Scoping Review

Limitations related to the SR and SSS production process are mainly linked to the methodological choices. Specifically:

1. The literature search covered a broad scope. However, it was constrained by language restrictions and limited to two bibliographic databases (Scopus and Web of Science), in line with the available resources.

2. Grey literature, including governmental documents, was excluded from the SR due to time and resource constraints. However, to ensure independent and objective evidence was prioritised.

3. Decisions to 1) exclude floating turbines (as described in the summary of the SSS) may have resulted in knowledge being missed in this regard; 2) focus on offshore wind farm infrastructure only likely led to impacts on coastal habitats being overlooked; 3) review articles were excluded due to time constraints and the complexity of handling aggregated data together with primary research data, which was the main focus; 4) regions outside of Europe (e.g., USA) may provide further insights on species that are relevant to certain EU regions.

4. The analytical approach to managing evidence that was relevant to multiple categories or addressed impacts across more than one MSFD descriptor (e.g., D1 and D7) was complex. When an article was deemed relevant to more than one descriptor, the paper was included in each applicable descriptor. While this is not a limitation per se, the final allocation of articles relied on the judgment and expertise of the reviewers. This also explains why retrieved knowledge on D1 is the greatest (e.g., an additional 24 publications were deemed relevant) (cf. ROSES diagrams that illustrate the literature allocation process).

5. In line with objectives, this current evidence synthesis identifies knowledge gaps and clusters, for each descriptor, regarding the impacts and cumulative impacts of OWF expansion on marine ecosystems and biodiversity. To this end, this approach may have resulted in the exclusion of published articles that concentrated solely on methodological innovation and exploring new approaches to capturing cumulative impacts. As a result, relevant contributions in methodological development may have been underrepresented in the review.

5.3.2 Participatory Workshop

The workshop supplemented the SR, provided rich information on new and/or unpublished approaches and projects that focused on spatially informed cumulative impacts. It also provided the opportunity to collectively review gaps across each cluster of descriptors and discuss current understanding of cumulative effects. We tried to avoid the limitations of one-off events by having pre- and post-workshop tasks to maximise participant input. These included sharing the SSS and briefing paper before the workshop, as well as sharing the draft report after the workshop for peer review. The involvement of a professional facilitator and support team, including Eklipse members (MEG, KCB and EMB) and authors of the SSS, meant that the workshop was well-resourced. The use of clusters also helped enable participants to gravitate towards areas of their expertise for more detailed discussions.

Finally, while the adopted approach provided an in-depth view of the knowledge gaps and the existing status of the research, we could not pursue or cover outputs such as modelling of cumulative impacts – these would require a significant understanding of gaps and pressures, which is currently limited.

Limitations for the workshop include:

1. The selective invitation of participants who were known to the EWG or were within the Eklipse network may have introduced bias in the perspectives represented. Due to time constraints and the highly technical nature of the request, which focused on synthesising formal scientific evidence, the participant pool could not be expanded to include representatives from Indigenous or local communities. As a result, the inputs may reflect a preference or bias toward scientific knowledge over observed evidence or lived experience.

2. The decision not to offer remuneration to workshop participants may have unintentionally biased participation toward individuals who are already salaried or institutionally supported and thus have the flexibility to engage without additional compensation.

3. The use of English as the primary language may have limited participants' ability to engage in real-time discussion and share or reference evidence published in other languages during the workshop. Additionally, the study summaries were also communicated in English.

4. Although efforts were made to recruit a diverse range of participants, the workshop was attended by 29 experts on the day. In addition to MEG, KCB and EMB members, and SSS authors. With four clusters planned, this reduced the intended group size by two participants per cluster. To mitigate potential imbalances or gaps, participants were invited to select two preferred clusters in advance. They were given the opportunity to change their allocation during the workshop if they wished.

5. The online format and limited duration (3.5 hours) also constrained the depth of participant engagement. However, efforts were made to maximise meaningful input through a pre-workshop task and a structured plenary discussion. The use of Mural enabled us to capture valuable participant information.

6. Conclusions

6. CONCLUSIONS

DG-Environment commissioned this report to further understand the cumulative impacts of fixed offshore wind farm foundations in relation to the 11 MSFD descriptors.

A scoping review of the available literature revealed substantial knowledge gaps. In particular, the geographical spread of the studies means that evidence is available for a subset of species relevant to those geographic areas, as well as for the life cycle of offshore wind farms and the understanding of cumulative impacts.

Several peer-reviewed modelling papers were reviewed as part of the study. These proved useful to investigate cumulative impact scenarios. However, the predictions remain to be verified and validated through long-term monitoring projects.

According to the reviewed literature, mitigation for individual descriptors and specific species appeared to be effective (one such example is the implementation of strict noise emission thresholds for D11C1 during construction). However, no studies have looked at strategies to mitigate cumulative impacts. Evidence gathering is a necessary stage before any strategies can be recommended for appropriate mitigation.

This report highlighted a clear need to develop monitoring and analysis guidelines or standards for assessing cumulative impacts and individual impacts (of a single wind farm) throughout its lifetime at the ecosystem level. This should be a top priority to ensure that data are collected and analysed to a comparable standard. Little progress can be made in assessing the cumulative impacts of OWFs until the comparability of studies is ensured.

A priority should be to invest in and mandate long-term monitoring, including assessment of mitigation measures, with a coordinated approach to gather data during **1)** all life cycles, plus a baseline, and **2)** covering potential impacts on multiple taxa is essential. Furthermore, key development areas should be identified, and within those, "indicator" sites should be selected to ensure a variety of habitats, species, and pressures can be assessed through these monitoring programmes. In addition to taxonomic-based approaches, incorporating functional traits and diversity into impact assessments provides a more universal and comparable framework for evaluating ecological consequences across regions. Future monitoring and analysis should prioritise the collection of functional trait data, enabling cross-basin comparisons and a more robust estimation of cumulative impacts on ecosystem functioning. A second priority should be to utilise the data collected during Phase 1 to verify and validate models, allowing them to be applied with a high degree of accuracy in future developments.

The report addressed three interpretations of the cumulative impacts of offshore wind developments: firstly, the interactions between wind farms and other human activities, secondly, the potential impacts arising from multiple wind farms, and thirdly, the cascading effects on the ecosystem. All these levels are relevant to the MSFD.

Fishing is the most represented activity assessed in cumulation to OWFs. More standardised methods would help integrate findings across case studies. It is necessary to deepen the knowledge base on multiple taxa, as current evidence mainly concerns birds and a single marine mammal species. So far, the main potential impact associated with multiple wind farms appears to be habitat loss. In this context, knowledge on population-level effects and long-range (cross-boundary) impacts is lacking. Quantifying whether the impacts of multiple wind farms are equal to, greater than, or smaller than the sum of their individual impacts will be key to future marine spatial planning. In this context, careful planning and predictive modelling could be useful for site selection. Similarly, cascading effects are poorly understood over large areas or from a cumulative perspective at the ecosystem scale. As a result, their duration is unknown. It is recommended that OWF sites and their impacts are investigated and integrated into quantitative and predictive studies to account for large-scale changes.

Scientific evidence of offshore wind farm impacts on the marine environment does not sufficiently cover the full lifecycle of a wind farm, the spatial scales that are relevant for cumulative impacts, or larger ecological compartments. Most impact studies typically cover only the most impactful activity at the individual level for a single species and for a single wind farm. Knowledge gaps identified in the short scientific summaries and during the participatory workshop include:

- **The collection of baseline data** for at least a year, durations longer than a few weeks, across spatial gradients of disturbance, to gather sufficient information on impacts
- **The use of standardised protocols** to compare results beyond single studies and sites, ideally following BACI and BAG approaches
- **The replicability of known OWF effects on all ecological compartments, key species groups and species** because evidence lies in a few areas across European waters and a few species (e.g., only one marine mammal species is well covered by the body of literature, and mostly from studies occurring in the Greater North Sea)
- **Detailed decommissioning information** at the EIA stage, including a detailed implementation plan with available technology that can be integrated closely to its execution, with new technologies that may become available. The report helped highlight a lack of studies covering all the life stages of offshore wind farms, from prospection to decommissioning, in current assessment frameworks.
- **Cumulative impacts at ecologically-relevant spatiotemporal scales** because it remains an emerging scientific field, and the evidence is still fragmented. The report highlighted difficulties in gathering evidence on potential or known cumulative impacts, which mirrors lessons learnt from other industries. However, empirical and modelling studies covering larger spatiotemporal scales, targeting multiple species and larger ecological compartments, are emerging and will help tackle this challenge.

To conclude, this report underscores the need for a comprehensive, long-term, and integrated approach to assessing and managing the impacts of offshore wind energy production at sea, including cumulative impacts on marine ecosystems. Significant gaps in knowledge persist, and addressing these gaps through improved monitoring, cross-disciplinary research, new and standardised assessment methodologies, and adaptive policy frameworks will be essential to ensure that Good Environmental Status across EU marine waters is achieved.

7. Acknowledgements

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8. References

8. REFERENCES

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9. Annexes

9. ANNEXES

Annexe 1 Ethical Considerations for Methods Protocol

The Eklipse process is built on a robust ethical infrastructure composed of twelve measures to mitigate potential ethical risks. In addition to protecting integrity and credibility, this ethical framework is crucial for the cooperation of actors from different spheres within a complex science-policy-society interface. In the context of activities undertaken by the EWG, the ethical framework applies and participants to the planned activities need to comply to the Eklipse Code of Ethics and tailored ethical measures need to be proactively set up before the activities start. Eklipse will be the body responsible for the overall administration and compliance of the ethical framework and tis procedures. Members of EMB, KCB and MEG will work collaboratively to ensure good practice is followed and the ethical procedures developed for the project are approved through the peer review process.

1. **Provide details of participant population and the number of participants required (Include brief characteristics as well as principal inclusion and exclusion criteria)**
The workshop will include five clusters (thematic areas) with up to six participants in each thematic area. Ideally, their expertise should cover all the identified gap areas and most of the 'combined' descriptors of GES used for the SSS and SR. Given the virtual nature of the workshop, experts from across the globe will be invited. Based on Eklipse's approach to mapping and gathering consent, individuals will be asked to sign a conflict-of-interest declaration, including their involvement in active projects that may be impacted by the outcomes of the report.

2. **Describe how and from where participants will be recruited.**
See the recruitment section above for details.

Identifying invited experts: Chosen experts would be from various sectors—academia, consultancy, NGOs, industry, and policymaking—with deep knowledge or experience on the given topic. Experts will also be selected from the 15 institutions identified initially as holding relevant expertise. EWG members will actively contribute by suggesting external experts, particularly recurring leading authors from the reviewed literature. Additionally, experts will be identified through consultations with organisations involved in related but separately timed reports, such as ICES, the European Environmental Agency, and IFREMER. The EWG will review the initial expressions of interest (EOIs) to identify experts who are interested and suitable for participation in this phase of the project.

3. Describe where the research activities will occur (for example, online, data collection tools being used, etc.)

The scoping review will be carried out using online databases. The participatory workshop will also take place online and will be delivered using Zoom. Workshop recording and Miro board will enable note taking and summarising, as well as help capture the essence of the discussions. Consent to record will be sought beforehand as part of the recruitment phase. As such, we will have written consent for recording, but crucially, participants will have the choice to remain anonymous in any reporting of their contributions.

4. Describe any incentive participants may receive for participation.

Participants will not be remunerated for their time to avoid financial motivations for participating that may bias their inputs. They will be given the option to either be named in the final report as contributors to the request or remain anonymous.

5. How will consent be obtained from or on behalf of participants? When, where and how?

The Eklipse group responsible for compliance to the ethical infrastructure will develop guidelines for seeking consent, incorporating consent forms and conflict-of-interest declarations as essential components of the recruitment process. These forms will address confidentiality issues, and outline key participation requirements including minimum time commitments, and a summary of the workshop objectives and structure.

6. How will consent be recorded?

Consent forms will be provided at the recruitment stage and collated by the EMB. Verbal consent will be sought for the recording before the workshop.

7. Describe any ethical issues and how these will be mitigated.

External consultants, stakeholders and other participants may face conflicts of interest due to previous or recent collaboration on projects or the inability to share unpublished work. EWG members will be asked to declare possible connections to these organisations/ individuals (e.g., financial, shareholding, personal relationship etc.) when offering suggestions for the workshop. The conflict-of-interest declarations can be reviewed by the Eklipse group responsible for compliance to the ethical infrastructure for this process and decisions to include or exclude participants can be made collectively by this group and the EWG.

8. How will the results from this study (including feedback to participants) be disseminated?

A draft report of the scoping review and a briefing paper will be shared with the workshop participants beforehand. The summary of notes from the workshop will be shared for initial review by participants. The focus group and workshop input will be integrated into the final report and circulated to participants.

9. Describe how the anonymity of participants and the confidentiality of data will be protected and the specific methods to be used for this, both through the research and in the dissemination of findings.

Consent forms will include questions on anonymity, and the nature of the request and publication of findings will be explained in the form, allowing the option for experts to be - or not to be - identified. Code-naming will be used, if necessary (e.g., reviewer X1).

10. Who will have access to identifiable information? Describe any potential use of the identifiable data by others.

Eklipse group responsible for compliance to the ethical infrastructure for this process will have access to identifiable information if they attend the workshop. A subgroup of the EWG will be tasked with the analysis of the data, and the RA will devote key time to this activity under mentorship by the MEG and KCB.

11. Are there any conditions under which privacy or confidentiality cannot be guaranteed, or if confidentiality is not an issue in this research, explain why.
See above for consent and anonymity. This research does not focus on private data or confidential information. However, workshop participants will also be encouraged to adhere to principles of confidentiality.

12. Describe the methods of data analysis, how data will be stored and how long data will be stored for
Data from the project is collated and safeguarded by Eklipse processes for data collection and storage. Google drive with secured sharing to the EWG, MEG, KCB members and EMB will be used to work with the collated data for the duration of the project. The data generated from the workshop will include recordings from Zoom and meeting notes.

13. Conflict of interest - Does the EWG or any other investigator/collaborator have any direct personal involvement (e.g., financial, share-holding, personal relationship, etc.) with the organisations/individuals involved that may give rise to a potential conflict of interest?
The EWG members will be asked again to declare such possible connections before suggesting experts for the workshop. The conflict-of-interest declarations can be reviewed by the EMB and decisions to include or exclude participants can be made collectively by the KCB, EMB, MEG and EWG.

14. Participant information sheet and participant consent form.
Due to the short-term nature of this request, these have not yet been finalised. These will be provided promptly for review based on Eklipse's design of forms for experts and previous enquiries. Consent forms will include questions on anonymity and the nature of the request and publication of findings will be explained in the form allowing the option for experts to be or not be identified. Code-naming will be used for anonymity (e.g., reviewer X1).

Annexe 2 Ethical approval

Ashoka Trust for Research in Ecology and the Environment
A Scientific and Industrial Research Organization, recognized by
The Department of Scientific Industrial Research, Ministry of Science and Technology, Govt of India
Royal Enclave, Srirampura, Jakkur Post, Bangalore – 560064
Ph: 91-80-23635555, Fax: 91-80-23530070, email: info@atree.org

Date: April 3, 2025

To,
Dr. Saloni Bhatia
Fellow
Ashoka Trust for Research in Ecology and the Environment
Bangalore

Sub: Approval from the Institutional Review Board (IRB)

This is concerning your application for the approval of IRB for the study titled **"Impacts of offshore wind farm expansion: what are the consequences for achieving Good Environmental Status across European marine waters?"**

The IRB has reviewed and approved your application as you are the lead contact for coordinating the IRB approval and part of the methods expert group for Eklipse.

Here is your IRB number for your future reference: **IRB/OTH/001/SBh/04/2025.**

You are hereby informed that your IRB approval is based on the methods and protocols specified in the application and approval of any changes in these will require fresh approval from the IRB.

Sincerely,

G. Ravikanth

Dr. G. Ravikanth
Chair - IRB

Ashoka Trust for Research in Ecology and the Environment ★ atree

Annexe 3: Literature searches

Table A3.1. Shows the search strings used for all literature searches undertaken in the SR based on descriptors of GES as stated in Article 8 of the ↗ European Commission Decision on GES 2017/848 document

DESCRIPTORS/ PRIMARY CRITERIA	SUB-GROUPS	KEYWORDS
D1-Marine biodiversity	Mammals	TS = (((bat$ OR mammal$ OR whale$ OR „Minke whale" OR „Sei whale" OR „Bryde's whale" OR „Blue whale" OR „Fin whale" OR „Northern right whale" OR „Humpback whale" OR „Short-finned pilot whale" OR „Long-finned pilot whale" OR „Shortfinned pilot whale" OR „Longfinned pilot whale" OR „Risso's dolphin" OR „Northern bottle-nose whale" OR „Northern bottlenose whale" OR „Pygmy sperm whale" OR „Sowerby's beaked whale" OR „Blainville's beaked whale" OR „Gervais beaked whale" OR „True's beaked whale" OR „Melon-headed whale" OR „Melonheaded whale" OR „Sperm whale" OR „False killer whale" OR „Cuvier's beaked whale" OR „Grey seal" OR „Mediterranean monk seal" OR „Ringed seal" OR „Common seal" OR „Harbour seal" OR „Harbor seal" OR „Short-beaked common dolphin" OR „Shortbeaked common dolphin" OR „Fraser's dolphin" OR „Atlantic white-sided dolphin" OR „Atlantic whitesided dolphin" OR „White beaked dolphin" OR „Killer whale" OR „Harbour porpoise" OR „Harbor porpoise" OR „Striped dolphin" OR „Atlantic spotted dolphin" OR „Rough-toothed dolphin" OR „Roughtoothed dolphin" OR „Bottle-nosed dolphin" OR „Bottlenose dolphin" OR „Dwarf sperm whale" OR „Blainville's beaked whale" OR „Fraser's dolphin" OR „Atlantic white-sided dolphin" OR „Atlantic whitesided dolp") AND („wind farm$ OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „Skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
	Birds	TS = (((birds$ OR seabird$ OR waterbird$ OR "Common sandpiper" OR Razorbill OR "Little auk" OR Pintail OR Shoveler OR Teal OR wigeon OR Mallard OR "Greenland white-fronted goose" OR "Greylag goose" OR "Lesser White-fronted Goose" OR "Eurasian rock pipit" OR "Ruddy turnstone" OR "Short-eared Owl" OR "Common pochard" OR "Tufted duck" OR "Greater scaup" OR "Brent goose" OR "Canada goose" OR "Barnacle goose" OR "Red-breasted Goose" OR "Common goldeneye" OR "Bulwer's petrel" OR Sanderling OR Dunlin OR "Greenland dunlin" OR "Red knot" OR "Curlew sandpiper" OR "Purple sandpiper" OR "Little stint" OR „Cory's Shearwater" OR "Scopoli's shearwater" OR "Black guillemot" OR "Pied kingfisher" OR "Kentish Plover" OR "Ringed plover" OR "Greater sand plover" OR "Black tern" OR "Black stork" OR "Long-tailed duck" OR "Bewick's swan" OR "Tundra swan" OR "Whooper swan" OR "Mute swan" OR "Little egret" OR "Eleonora's falcon" OR "Peregrine Falcon" OR Puffin OR Coot OR "Northern fulmar" OR "White-billed diver" OR "Black-throated diver" OR "Great northern loon" OR "Red-throated loon" OR "red-throated diver" OR Oystercatcher OR "White-throated kingfisher" OR "white-tailed sea-eagle" OR "Black-winged stilt" OR "European storm petrel" OR "Mediterranean storm petrel" OR "Little gull" OR "Herring gull" OR "Armenian Gull" OR "Audouin's gull" OR "Common gull" OR "Lesser black-backed gull" OR "Slender-billed gull" OR "Iceland gull" OR "Glaucous gull" OR "Great black-backed gull" OR "Mediterranean gull" OR "Yellow-legged gull" OR "Little gull" OR "Black-headed gull" OR "Bar-tailed godwit" OR "Black-tailed godwit" OR "Velvet scoter" OR "Common scoter" OR skew OR "Common merganser" OR goosander OR "Red-breasted merganser" OR "Northern gannet" OR Curlew OR whimbrel OR "Slender-billed Curlew" OR "Band-rumped Storm-Petrel" OR "Leach's storm petrel" OR "Monteiro storm-petrel" OR "Ivory gull" OR Osprey OR "Bearded Reedling" OR "White-faced storm petrel" OR "Dalmatian Pelican" OR "Great White Pelican" OR "White Pelican" OR "European shag" OR "Mediterranean shag" OR "Great cormorant" OR "Pygmy cormorant" OR "Grey phalarope" OR "Red-necked phalarope" OR Ruff OR "American flamingo" OR "Eurasian spoonbill" OR "Glossy Ibis" OR "Golden plover" OR "Grey plover" OR "Slavonian grebe" OR "Great crested grebe" OR "Red-necked grebe" OR "Black-necked grebe" OR "Steller's eider" OR "Desertas petrel" OR "Fea's petrel" OR "Zino's petrel" OR "Little shearwater" OR "Barolo shearwater" OR "Great shearwater" OR "Sooty shearwater" OR "Audubon's shearwater" OR "Balearic shearwater" OR "Manx shearwater" OR "Mediterranean shearwater" OR "Yelkouan shearwater" OR "Pied avocet" OR "Black-legged kittiwake" OR "Common eider" OR "King eider" OR "Long-tailed skua" OR "Arctic skua" OR "Pomarine skua" OR "Great skua" OR "Lesser Crested Tern" OR "Caspian tern" OR "Roseate tern" OR "Common tern" OR "Gull-billed tern" OR "Sandwich tern" OR "Arctic tern" OR "Little tern" OR "Rosy Starling" OR "Little Grebe" OR "Ruddy Shelduck" OR Shelduck OR "Spotted redshank" OR "Wood sandpiper"
	Reptiles TS	= (((reptile$ OR „sea turtle$" OR „loggerhead turtle" OR „green turtle" OR „leatherback turtle" OR „hawksbill turtle" OR „kemp's ridley turtle") AND („wind farm$ OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))

DESCRIPTORS/ PRIMARY CRITERIA	SUB-GROUPS	KEYWORDS
	Cephalo-pods	TS = (((cephalopod$s OR squid$ OR octopus OR cuttlefish OR „Curled octopus" OR „Musky octopus" OR „Shortfin squid" OR „Inshore squid" OR „European squid" OR „Common octopus" OR „Giant African Cuttlefish" OR „Common cuttlefish" OR „Pink cuttlefish" OR „Flying squid" OR „Lesser flying squid") AND („wind farm$ OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „Skagerak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
	Fish	TS = ((((fish AND coastal OR pelagic OR demersal OR deep) OR anchovy OR anglesharp OR angler OR anglerfish OR antimoral OR bandish OR barracuda OR bigeye OR blenny OR bluefin OR bream OR brook OR bullhead OR catshark OR chub OR cod OR comber OR conger OR dab OR dentex OR dogfish OR dolphinfish OR dory OR drum OR eel OR filefish OR flounder OR forkbead OR goby OR greeneyi OR grenadier OR grouper OR grunt OR gulper OR gurnard OR hake OR halibut OR hammerhead OR herring OR hagfish OR killifish OR lamprey OR ling OR loach OR mackerel OR mako OR meagre OR megrim OR minnow OR moray OR mullet OR perch OR picardy OR pike OR pilchard OR pipefish OR plaice OR pomfret OR pout OR rabbitfish OR ray OR redfish OR rockfish OR rocking OR rockfish OR roughstalk OR roughy OR salmon OR sandeel OR sardinella OR saury OR sawfish OR scabbardfish OR scaleback OR scalefish OR scorpionfish OR sculpin OR seabass OR seabream OR seahorse OR seasnails OR sevengill OR shad OR shark OR monkfish OR sigill OR skate OR slickheads OR slimeheads OR snipefishes OR snouted OR sole OR spiny OR spotted OR sprat OR spurion OR stargazer OR starry OR stickleback OR stingray OR sturgeon OR sunfish OR tiger OR toadfish OR toothcarp OR topknots OR torpedo OR trout OR tuna OR tenny OR weever OR whitefish OR whiting OR wolffish OR wrasse OR yellowtail)) AND („wind farm$ OR windfarm$ OR „wind energy" OR „wind park$" OR „windpark$" OR „wind power station$" OR wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea"))
D2-NIS		TS = (((species NEAR/15 „non-indigenous" OR alien OR exotic OR „non-native" OR allochthonous) AND („wind farm$ OR windfarm$ OR „wind energy" OR „wind park$" OR „windpark$" OR „wind power station$" OR wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „Skagerak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
D3-Commercial fish and shellfish		TS = (((fisheries OR stock$ OR „commercially exploited fish and shellfish" OR („commercially exploited" NEAR/15 fish OR shellfish)) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
D4-Food Web		TS = (((„food web$ OR „food chain$" OR „trophic web$" OR „trophic level$ OR autotroph$ OR heterotroph$ OR phytoplankton OR diatoms OR dinoflagellates OR mesozooplankton OR copepods OR cladocerans OR „benthic filter-feeding invertebrate$" OR „benthic feeding invertebrate$" OR „planktivorous fish" OR „planktivorous invertebrate$" OR „sub-apex pelagic predator$" OR predator$ OR „sub-apex demersal predator$" OR „apex marine mammal predator$" OR „apex predator$" OR „apex fish predator$") AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „Skagerak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
D5-Eutrophication		TS = (((nutrient$ OR nitrogen OR „dissolved inorganic nitrogen" OR DIN OR phosphorus OR „dissolved inorganic phosphorus" OR DIP OR „total phosphorus" OR TP OR „total nitrogen" OR TN OR „chlorophyll-a" OR „phytoplankton biomass" OR „dissolved oxygen" OR „harmful algal bloom" OR HAB OR cyanobacteria OR dinoflagellates) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „Skagerak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))

DESCRIPTORS/ PRIMARY CRITERIA	SUB-GROUPS	KEYWORDS
D6-Seabed integrity		TS = (((„seabed integrity"OR morphology OR „ecosystem loss" OR „habitat loss" OR substrate OR sediment* OR (abrasion OR dredg* OR „physical loss" OR „physical disturbance" OR damage OR degradation NEAR/5 seabed OR seabottom OR seafloor OR benthic)) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
D7-Hydrological conditions		TS = (((„hydrographical condition$" OR „hydrographical regime$" NEAR/15 temperature OR salinity OR current$ OR wave$ OR turbidity OR bathymetry OR tide$ OR wake OR stratification) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR
D8-Contaminants TS		TS = (((contaminant$ OR metal$ OR lead OR cadmium OR mercury OR copper OR polyaromatic OR hydrocarbon$ OR PAH$ OR „perfluorooctane sulfonate$" OR PFOS OR „hexabromocyclododecane" OR HBCDD OR „polybrominated diphenyl ether$" OR PBDE$ OR „polychlorinated biphenyl$" OR PCB$ OR dioxin$ OR furan$ OR tributyltin OR TNT OR „cesium-137" OR PFAS OR „organochlorinated pesticide$" OR lindane OR aldrin OR dieldrin OR HCB OR DDT$ OR heptachlor) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
D9-Contaminants in Food		TS = ((((contaminant*) NEAR/15 (seafood OR lead OR cadmium OR mercury OR dioxins OR PCB$ OR PAH$)) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „Skagerak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
D10-Marine litter		TS = (((debris OR scrap OR pollution OR waste OR litter OR plastic$ OR rubber OR cloth OR textile OR paper OR cardboard OR „processed wood" OR glass OR ceramic$ OR chemical$ OR „single-use plastic$" OR microlitter OR microplastic$ OR particle$) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))
D11-Energy and Noise		TS = (((vibration$ OR noise$ OR sound$ OR light OR „electromagnetic field$" OR decibel$ OR drilling OR piling OR „pile driving" OR „soft-start" OR „hydro sound damper" OR „hammer energy" NEAR/15 „man-made" OR anthropogenic OR „long lasting" OR continuous OR „short duration" OR „masking auditory" OR underwater OR impulsive OR intermittent OR „high frequency" OR „low frequency" OR intensity) AND („wind farm$" OR windfarm$ OR „wind energy" OR „wind park$" OR windpark$ OR „wind power station$" OR „wind power plant$" OR „wind turbine$") AND („baltic sea" OR „north sea" OR „kattegat" OR „skagerrak" OR „English channel" OR „celtic sea" OR „bay of biscay" OR „iberian coast" OR „macaronesia" OR „mediterranean sea" OR „ionian sea" OR „tyrrhenian sea" OR „adriatic sea" OR „aegean sea" OR „levantine sea" OR „ligurian sea"OR „black sea")))

Annexe 4 Scoping process

4.1 Eligibility Criteria

Table A4.1. Shows the defined set of inclusion and exclusion criteria, following the PerSPEcTiF question framework in Table 2.

CRITERIA ACCORDING TO THE PerSPEcTiF FRAMEWORK			DESCRIPTION
Inclusion criteria	*Eligible Perspective*		All peer-reviewed literature on single impacts and/ or cumulative impacts of OWFs on the achievement of GES published only in the English language. Other languages are beyond the scope of these SSS.
	Eligible setting		Only literature based on the European regional seas as defined by the EU MSFD.
	Phenomenon of interest	*Eligible subject*	As defined by the EU MSFD, all species groups and habitats defined across 11 descriptors (D01-D11): **D01:** marine birds, marine mammals, marine reptiles, fish, and cephalopods native to EU waters will be retained. N.B., bats will be included as mounting academic literature is also revealing impacts on this flying vertebrate group. **D02:** non-indigenous species (NIS) introduced by OWF activities that impact native marine biodiversity and ecosystems. **D03:** populations of commercial fish and shellfish species impacted by OWFs. **D04:** ecosystems, including food webs impacted by OWFs. **D05:** algae blooms and oxygen deficiency in EU waters **D06:** physical loss (or permanent change) of all-natural seabed habitat types, resulting from the anthropogenic pressure of OWFs, including connection cables **D07:** hydrographical conditions (e.g. changes in wave action, currents, salinity, temperature) to the seabed and water column. **D08:** pollutants/ contaminants, i.e., 'synthetic compounds, non-synthetic substances and compounds liable to cause pollution'. This includes all substances (i.e., chemical elements and compounds) or groups of substances that are toxic, persistent and liable to bio-accumulate. **D09:** contaminants in edible tissues (muscle, liver, roe, flesh or other soft parts) of seafood (including fish, crustaceans, molluscs, echinoderms, seaweed and marine plants) caught or harvested in the wild. **D10:** any persistent, manufactured or processed solid material that is discarded, disposed of, or abandoned in the marine and coastal environment **D11:** any introduction of energy, including underwater noise, both continuous and impulsive sources, caused by OWFs as described in MSFD
		Eligible Exposure	All fixed-bottom offshore wind turbines across life-cycle stages:
	Eligible Findings		Relevant findings in line with the existing primary assessment criteria of the MSFD: **Findings 1:** Single direct impacts of OWFs on marine biodiversity and ecosystems. **Findings 2:** Cumulative impacts (e.g., combined, repetitive, and interactive impacts) that may result from OWF activities over time and space. N.B. not all qualifying documentation requires reporting both types of impacts simultaneously.

CRITERIA ACCORDING TO THE PerSPEcTiF FRAMEWORK			DESCRIPTION
	Eligible Environment		Marine environment, including coastal zone to open ocean.
	Eligible Timing		All relevant evidence will be considered since the ratification of the MSFD (Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008), i.e., 2008 – to present.
	Eligible language		English.
Exclusion criteria	*Ineligible setting*		All studies outside of the European Union's regional seas.
	Phenomenon of interest	*Ineligible subject*	All terrestrial wild species/domestic species will not be retained.
		Ineligible Exposure	Any renewable energy other than OWFs. i.e., all on-shore wind farms, and all photovoltaic parks. Also, floating wind parks are not included in this current study.
	Ineligible environment		All evidence focused on terrestrial species and habitats.
	Ineligible Timing		All evidence published before 2008 will not be considered for Scoping review purposes.
	Ineligible language		All, except English.
	Ineligible findings		Any mention of results other than single direct impacts or cumulative impacts of OWFs on descriptors' subjects.

4.2 Data extraction and synthesis

The following data - from the retained scientific literature - were extracted into online Google Sheets, which were used to produce Short Science Summaries (SSS). NB a separate Google sheet was created for each GES descriptor. To ensure data was extracted in a repeatable, objective, and structured manner, the following attributes listed below were extracted, following the PerSPEcTiF framework.

Perspective characteristics:

- Publication source
- Type of publication (e.g. journal article, book chapter, conference proceeding)
- Publication details (i.e., title, authors, publication year, DOI)
- Time frame: data collection period, i.e., when were data collected (different from publication year)

Setting characteristics:

- Geographical location, according to the MSFD regional and sub-regional seas (e.g. Baltic Sea, Black Sea, Mediterranean Sea and North East Atlantic - North Sea, Bay of Biscay, Celtic Sea, Iberian Coast).
- Ecosystem type, related to major biological zones (depth) and substrate type, according to the EUNIS level 2 Classification: A1—Intertidal rock and other hard substrates; A2—Intertidal sediment; A3—Subtidal rock and other hard substrates; A4—Circalittoral rock and other hard substrates; A5—Subtidal sediment; A6—Deep-sea habitats; A7—Pelagic habitats; A8—Ice-associated marine habitats+free space for others ecosystem types.
- Specific ecosystem, based on Campagne et al. 2023: Tidal marsh, Seagrass; Reef habitats, Kelp forests; Estuary+free space for other specific ecosystem types.

Phenomenon of interest characteristics:

› **Subject of interest:**

- Species groups, habitats impacted.
  - whether: pelagic, benthic, and other
  - if migratory species: yes, no.
  - seasonal habitat due to migration from feeding, mating and/ or nursery ground

› **Exposure characteristics:**

- Type of wind farm turbines causing impacts (following Rezaei et al. 2023 typology):
  - Fixed-bottom offshore wind turbines: (i) Monopile; (ii) Tripod; (iii) Jacket; (iv) Suction caisson; (v) Gravity base; (vi) Tripile; (vii) Twisted jacket.

Findings' characteristics:

› **Characterisation of the pressures-impacts** relationship for each GES descriptor.

- Relative to three different lifecycle stages: 1) installation, 2) operation, and 3) decommissioning Evidence of impact measured or observed (i.e. relating to individual GES descriptors)
  - **D01:** Changes in studied biodiversity group with regards to wind farm expansion (e.g. Birds, Mammals, Fish, Cephalopods - Indigenous sp. only, benthic and pelagic habitats)
  - **D02:** Changes in composition of native marine communities, displacement of native species due to the introduction of Non-indigenous species by wind farm expansion
  - **D03:** Studies covering commercial fish and/or shellfish impacted by OWF expansion.
  - **D04:** Food webs (e.g. describe impacts on linkages between living organisms caused by wind farm expansion)
  - **D05:** Eutrophication (e.g. describe impacts on chlorophyll a, phytoplankton biomass, primary production, dissolved oxygen and nutrient dynamics)
  - **D06:** Seabed integrity (e.g. describe impacts such as physical disturbance and loss of habitat due to wind farm expansion, including from connection cables)
  - **D07:** Hydrological conditions (e.g. describe impacts to physical parameters of seawater: temperature, salinity, depth, currents, waves, and turbidity due to wind farm expansion)
  - **D08:** Contaminants (e.g. describe impacts of contaminants associated with wind farm expansion that degrade the marine environment)
  - **D09:** Contaminants in seafood (e.g. describe impacts of contaminants in seafood caused by the expansion of wind farms)
  - **D10:** Marine litter (e.g. describe impacts related to litter such as mortality entanglement)
  - **D11:** Underwater noise (e.g. describe impacts associated with electricity systems, noise, electromagnetic radiations, vibrations, among others related to wind farm expansion)

Additional characteristics

› **Study type:** 1) Observational, 2) Experimental

› **Study design:** Control-Impact (CI) (reference site or site comparison), Before-After (BA) (temporal comparison), After only (multiple points in time), Before-After-Control-Impact (BACI), gradient sampling design, or No comparator.

› **Lastly,** where any of the above information was not specified in the retained literature, it was coded as "Unspecified".

Annexe 5 Workshop participants

Table A5.1: Full workshop participant registration list

WORKSHOP PARTICIPANT	INSTITUTION
Christopher Sweeting	Marine Management Organisation
Claire	Plymouth Marine Laboratory
Gert Van Hoey	ILVO
Giacomo Ottaviano Andrea Montereale Gavazzi	European Commission Joint Research Centre
Gordon Watson	University of Portsmouth
Jan Schmidtbauer Crona	Swedish Agency for Marine and Water Management
Olivier Delmas	INERIS
Angel Borja	AZTI
Peter Heslenfeld	Rijkswaterstaat
Tanja Kögel	Institute of Marine Research, Bergen, Norway
Sophia Yakoob	Marine Management Organisation
Emily Corcoran	Consultant to SPF Belgium, Marine Environment Department
Anna Ebeling	Helmholtz-Zentrum Hereon
Eda Bayar	EXPERT- EUROPEAN ENVIRONMENT AGENCY
Ida Carlén	Swedish Society for Nature Conservation
Niels van Houten	Dutch
Jim Masters	Defra
Jelle Rienstra	Deltares
Miranda Willis	MMO
Ljuba Ferrario	Seas At Risk
Devi Veytia	Ecole Normale Superieur
Sybill Henry	France Energies Marines
Beth Scott	University of Aberdeen
Juan Camilo Cubillos Moreno	Thuenen Institute for Sea fisheries
Mathilda Karlsson	WWF Sweden
Joana Matias	DGRM
Silvia Monteiro	Universidade de Aveiro
Heliana Teixeira	CESAM & Dept. of Biology, University of Aveiro
Nathalie Niquil	Centre National de la Recherche Scientifique (CNRS)
Marcela Velasco Gomez	Joint Research Centre - European Commission
Paris Vasilakopoulos	Joint Research Centre - European Commission

Table A5.2: showing the type of institutions represented by the experts participating in the workshop

TYPE OF INSTITUTION	NUMBER OF PARTICIPANTS
Research	11
Government	10
NGO	3
Education	3
International organisation	1
European Commission	1

Annexe 6 Workshop agenda

Online Workshop: "Impacts of offshore wind farm expansion: what are the consequences for achieving Good Environmental Status across European marine waters?"

April 10th 2025 – 09:30 – 13:00 CEST - by invitation only

Zoom link:

Agenda

Introduction Background and Objectives (10 minutes)

- Welcome to participants
- Workshop objectives and agenda

Summary of the Report and Results (20 minutes)

- Presentation of the key findings and conclusions from the report (15 minutes)
- Q&A and brief discussion on the report (5 minutes)

Thematic Area Discussions (60 minutes)

- Breakout Groups: Knowledge Gaps and Key Results
- Participants will be divided into four thematic breakout groups based on areas of interest or expertise

  Group 1: (D1 mammals, birds, D11), Topic: Noise, birds and mammals
  Group 2: (D1 benthic habitats, D2, D5, D6; Topic: Habitats and seabed integrity
  Group 3: (D1 fish & cephalopods, D3, D4, D7); Topic: Fish, fisheries, and food webs
  Group 4: (D8, D9, D10) Topic: Contaminants and litter

COMFORT BREAK (15 mins)

Reporting from the groups (20 minutes)

Plenary Session: Reflection of results (1h 10 minutes)

- Reactions to the group result
- Discussion of common challenges, opportunities, and cross-cutting issues
- Reflective Panel

Plan for action, conclusion and next steps (15 minutes)

- Final comments and acknowledgement of contributions
- Recap of the next steps and closing

Annexe 7 Workshop information (mural info)

Link to the workshop material:
↗ https://eklipse.eu/wp-content/uploads/2025/09/Material-worshop-OWF-re-querst-April-2025.pdf

Annexe 8 Workshop information references per cluster

Cluster 1: D1 (mammals and birds); D11: Energy, including underwater noise.

Descriptor 1

Allen, S., Banks, A. N., Caldow, R. W. G., Frayling, T., Kershaw, M., & Rowell, H. (2020). Developments in understanding red-throated diver responses to offshore wind farms in marine Special Protection Areas. In Marine Protected Areas (pp. 573–586). Elsevier. ↗ https://doi.org/10.1016/B978-0-08-102698-4.00029-0

Declerck, M., Trifonova, N., Hartley, J., & Scott, B. E. (2023). Cumulative effects of offshore renewables: From pragmatic policies to holistic marine spatial planning tools. Environmental Impact Assessment Review, 101, 107153. ↗ https://doi.org/10.1016/j.eiar.2023.107153

Degraer, S.; Brabant, R.; Rumes, B.; Vigin, L. (2023). Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Progressive Insights in Changing Species Distribution Patterns Informing Marine Management. Report by Royal Belgian Institute of Natural Sciences (RBINS)

Gigot, M., Tremblay, R., Bonnel, J., Mathias, D., Meziane, T., Chauvaud, L., & Olivier, F. (2024). Noise pollution causes parental stress on marine invertebrates, the Giant scallop example. Marine Pollution Bulletin, 203, 116454. ↗ https://doi.org/10.1016/j.marpolbul.2024.116454

Gill, A., & Desender, M. (2020). 2020 State of the Science Report, Chapter 5: Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices (No. PNNL--29976CHPT5, 1633088; p. PNNL--29976CHPT5, 1633088). ↗ https://doi.org/10.2172/1633088

Marmo, B. (2013). Modelling of Noise Effects of Operational Offshore Wind Turbines including noise transmission through various foundation types: Scottish Marine and Freshwater Science Vol 4 No 5. Marine Scotland Science. ↗ https://doi.org/10.7489/1521-1

Quéroué, M., Authier, M., Besnard, A., & Heerah, K. (2024). Going digital: Challenges in monitoring marine megafauna when comparing results from visual and digital aerial surveys. Frontiers in Marine Science, 11, 1432798. ↗ https://doi.org/10.3389/fmars.2024.1432798

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Descriptor 11

OSPAR Commission. (2015). Guidelines to reduce the impact of offshore installations lighting on birds in the OSPAR maritime area (OSPAR Agreement 2015-08).

Dyndo, M., Wiśniewska, D. M., Rojano-Doñate, L., & Madsen, P. T. (2015). Harbour porpoises react to low levels of high frequency vessel noise. Scientific Reports, 5(1), 11083. ↗ https://doi.org/10.1038/srep11083

Kok, A. C. M., Berkhout, B. W., Carlson, N. V., Evans, N. P., Khan, N., Potvin, D. A., Radford, A. N., Sebire, M., Shafiei Sabet, S., Shannon, G., & Wascher, C. A. F. (2023). How chronic anthropogenic noise can affect wildlife communities. Frontiers in Ecology and Evolution, 11, 1130075.
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↗ https://doi.org/10.3389/fmars.2023.1129057

Cluster 2: D1 (Benthic habitats), D2: Non-indigenous species, D5: Eutrophication, D6: Sea bed Integrity.

Descriptor 2

Dauvin, J.-C. (2024). Do offshore wind farms promote the expansion and proliferation of non-indigenous invertebrate species? Marine Pollution Bulletin, 206, 116802.
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Descriptor 5

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CLUSTER 3: D1 (fish & cephalopods), D3 (fisheries), D4 (Food webs), D7 (Hydrological conditions)

Descriptor 3

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Descriptor 4

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CLUSTER 4: D8 (contaminants); D9 (Contaminants in seafood), D 10 (marine litter)

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Descriptor 9

Ongoing project OLAMUR will analyze some blue mussels for contaminants in pilot windfarms to investigate multi-use of area with seafood (macroalgae and blue mussel farming.
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