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Evidence mapping of the causes and effects of habitat change attributed to offshore wind development is important for determining impacts on fisheries species

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Abstract

As offshore wind (OSW) developments continue to expand globally, so does their interaction with fisheries. When assessing these interactions, it is important to understand how fisheries species are impacted, yet the evidence base linking OSW habitat change to fisheries species impacts is limited. The holistic Driver-Activity-Pressure-State-Impact-Response (*DAPSIR*) framework was used to map how pressures associated with OSW construction and operation could cause specific changes in state of the environment and consequential impacts on fisheries species. The framework was adapted to separate out ecological and population impacts. This separation was required to understand the sequence of steps associated with OSW habitat change through to localised impacts on fisheries species and then towards potential population level impacts; these are needed to predict the consequential impacts on fisheries, fishers and society. Multiple Cause–Effect pathways linking the elements of the framework, focussing specifically on the pressure, state changes and ecological impacts on fisheries species were tabulated, based on expert elicitation. The literature was searched to identify where there was direct evidence to support these predicted pathways and where there were gaps in the evidence base associated with determining the ecological impact. The assessment highlighted that most of the published evidence searched focused on the pressures created due to OSW and the associated state changes to the marine environment. Meanwhile, there was limited evidence demonstrating how the identified pressures and state changes in the habitat subsequently impacted fisheries species. These gaps should be filled to be able to assign the causes and effects of OSW habitat changes to the impacts on fisheries species that are meaningful and relevant at the level of

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fisheries populations. Setting out the Cause–Effect pathways between habitat change associated with OSW developments and separating out the ecological impacts on fisheries species and potential to have population impacts allowed us to correctly assign the evidence available to steps in the *DAPSIR* framework. This is important to ensure greater confidence in the scientific evidence used to inform management of OSW developments in relation to impacts on fisheries species, their populations, and therefore fisheries. (i.e. the human impact).

Keywords offshore renewable energy, habitat alteration, DAPSIR, ecological impact, fisheries impacts

Introduction

Planning and establishment of offshore wind (OSW) energy developments is increasing across the globe, with national targets for renewable energy production and net zero emissions growing in efforts to mitigate climate change and energy security risks (Williams et al. 2025). The marine areas allocated for OSW often overlap with important commercial and recreational fisheries (Gill et al. 2020, Gimpel et al. 2023). This convergence of OSW and fisheries areas can displace fishing activities from traditional fishing grounds, alter vessel routes and lead to spatial squeeze on other fishing grounds (Campbell et al. 2025, Szostek et al. 2025). A critical aspect that will fundamentally affect fisheries is the outcome of interactions between OSW and the fisheries species and resultant impacts. Evidence of how fisheries species are affected by environmental changes attributable to OSW development and the consequent impact on their populations is limited (Gill et al. 2025). This limitation in the available evidence for determining how the installation and operation of OSW turbines affect local habitat with consequences for fisheries species remains an important challenge to address (Gill et al. 2025), as changes to the fisheries species could have cascading effects on the fishers in terms of catches and fishing areas. Here, we present an approach focused on assessing the effects of introducing new physical habitat through OSW infrastructure on fisheries species. We emphasize that potential changes must be clearly evidenced through ecological outcomes before determining population-level impacts on fisheries species. The approach has the advantage that it is based on an already established framework [i.e. Driver-Activity-Pressure-State-Impact-Response (*DAPSIR*); Elliott et al. 2017] and is directly applicable to assessments of the potential impacts of other human activities on fisheries species and their populations (Oesterwind et al. 2016).

Over the past three decades, OSW has been dominated by seabed fixed technology, with development in general occurring in four phases: pre-construction (lasting several years), construction (also spanning several years), operation (∼25–30 years), and decommissioning (estimated to take a few years), noting that the length of each phase will depend on project and site-specific factors (see Lifecycle overview, Guide to an Offshore Wind Farm 2025). Each phase introduces distinct pressures on the local marine ecosystem (Gill 2005, Degraer et al. 2020b, Bergström et al. 2013). Reviews of the literature highlight the potential for OSW-related pressures to disrupt the behaviour, distribution, abundance, reproduction, and survival of fisheries species during one or more of these phases (Krone et al. 2013, Reubens et al. 2014a, Hogan et al. 2023, Gill et al. 2025). These disruptions are predicted to affect fisheries species production with potential secondary or "knock-on" impacts on the sustainability of fish populations, and therefore consequences to fisheries (Hogan et al. 2023).

Groupings of fisheries species affected by OSW include but are not limited to teleost fish, elasmobranchs, cephalopods, and shellfish. Each of these taxonomic groups represent fisheries species with diverse life histories and behavioural traits that depend on different areas of the marine and coastal environment (pelagic, demersal, benthic) and the habitats within them for different parts of their life cycle (i.e. spawning, egg/larval, and juvenile development), feeding, and shelter (Secor et al. 1992, Kaiser et al. 2011). The installation and operation of OSW turbines inevitably alter the existing habitats of fisheries species, adding new pressures to existing ones, such as fishing, climate change, and those from other human activities. This highlights the importance of understanding OSW-specific pressures in the context of other existing pressures in order to determine if the OSW infrastructure has specific impacts on fisheries species.

Previous studies on the habitat changes associated with the installation and operation of fixed OSW developments have shown marked effects on the benthic community through colonization and species use of the OSW structures and the adjacent seabed (Degraer et al. 2020a, Mavraki 2020). A series of Cause–Effect pathways link the installation and presence of the wind turbine infrastructure to these benthic changes, which then can have consequences for ecological structure and functions (Coates et al. 2015, Dannheim et al. 2019) and the ecosystem service of benthic species caught for food (Szostek et al. 2025). Habitat changes associated with OSW infrastructure construction and operation are not limited to the benthic environment, but can also alter the water column, potentially affecting demersal and pelagic fisheries species. Therefore, determining the habitat changes and the Cause–Effect pathways between OSW developments and all fisheries species and appraising the available evidence is essential in order to attribute impacts from OSW infrastructure (Gill et al. 2020).

The installation of fixed OSW introduces artificial hard structures onto the seabed and into the water column up to the sea surface. This new hard substratum is colonized by benthic-associated species, which interact with fisheries species (Degraer et al. 2020a). The resulting increases in the biodiversity and biomass of benthic macrofauna represent more prey resources for some fisheries species near wind turbines, which could lead to new predator-prey interactions and therefore effects on the food web (Degraer et al. 2020a, Lefaible et al. 2025). For example, studies in the southern North Sea have reported specific age groups of Gadoids (e.g. Atlantic cod, *Gadus morhua*) feeding upon OSW-associated epifaunal species (Reubens et al. 2014b) as well as flatfish near the turbines adapting their diet to feed on crustaceans and other organisms typically associated with hard-substrata (Mavraki et al. 2021, Buyse et al. 2022). The aggregation of these organisms introduces organic matter in the proximity of turbines (Coates et al. 2014) that enriches the local community and can further enhance benthic macrofaunal biodiversity and functional richness (Lefaible et al. 2025). OSW infrastructure can also facilitate the colonization and spread of opportunistic species, some of which are regarded as invasive (Viola et al. 2018).

In sedimentary seabed areas, which have seen most OSW installations to date, a significant amount of seafloor disruption can occur during construction activities involving pile driving and cable laying, leading to increased local turbidity (Bailey et al. 2024), which could have consequences for visual predators, of which many species are fished. Any impacts will be species-specific and may also differ between life stages, with the effects dependent on the intensity and duration of the disturbance. Suggested impacts include visual impairment in adult stages and smothering of eggs and larvae through increased particulate matter in suspension, behavioural responses, and habitat modification (van Berkel et al. 2020). Understanding how these physical benthic changes affect species, biomass, behaviour and diversity near OSW clearly should be considered when assessing the impacts on fisheries species.

Several studies have demonstrated hydrodynamic changes following the installation of fixed wind turbines, especially in coastal, tidally driven environments as they disrupt natural interactions between the seabed and hydrodynamic processes (Austin et al. 2025, Hu et al. 2025). Fixed jacket and monopile foundations interact with the tidal currents creating downstream wakes of increased turbulence throughout the water column (Floeter et al. 2017, Miles et al. 2017, Schultze et al. 2020, Hendriks et al. 2025). Wakes are also associated with increased suspended particulate matter at the sea surface occur owing to the increase of turbulence in the current flow encountering the structure (e.g. Hansen et al. 2007, Bailey et al. 2024, Lecordier et al. 2025). The associated greater vertical mixing can affect stratified conditions along turbulent wakes, with a reduction of horizontal water velocity in the proximity of the turbine (Carpenter and Guha 2024). Another main effect relates to operating wind turbines altering the atmosphere-sea surface interaction along so-called "wind wakes" (e.g. Ludewig 2015), which creates areas of upwelling and downwelling in the proximity of the OSW development area (Floeter et al. 2022). In addition, both the below surface turbine foundations and the above surface wind energy extraction interfere with the hydrodynamic processes changing turbulent conditions, sediment resuspension, and nutrient distribution, as well as biotic properties of the water column (Schultze et al. 2020, Floeter et al. 2022). At larger scales, alterations to primary production are likely to be driven by changes in vertical stratification and nutrient distribution, potentially leading to redistribution of food available for fisheries species (Akhtar et al. 2021, Daewel et al. 2022, Zampollo et al. 2025). Hydrodynamic processes and stratification are therefore key factors influencing food availability, spawning, migration, local movement routes and refugia of many species. Alteration of these processes can be predicted to impact fisheries species (van Berkel et al. 2020, Chen et al. 2024), therefore hydrodynamic-related environmental changes need to be considered with regard to Cause–Effect pathways relevant to fisheries species.

In terms of the changes to the sensory environment of fisheries species, the first phase of OSW development can generate significant underwater noise particularly during construction, as a consequence of dredging, pile driving and cable installation and sometimes the pre-construction seismic surveys (Mueller-Blenkle et al. 2010, Mooney et al. 2020). Once operational, turbines generate underwater noise at a lower intensity than construction-related noise, however this is a long-term noise source throughout the lifespan of the OSW site (Wahlberg and Westerberg 2005, Mooney et al. 2020). Underwater noise can impact fish and invertebrates through either particle motion or for some species sound pressure too (Popper and Fay 2011, Sigray and Andersson 2011, Popper and Hawkins 2018). Benthic fish and invertebrates may also be sensitive to vibrations caused by sound energy entering the substratum (Hawkins et al. 2021). Anthropogenic noise effects on fisheries species can include stress and behavioural changes, masking of reproduction-related sounds, temporary or permanent threshold shifts in hearing, injury and in some cases mortality (Dooling et al. 2015, Popper and Hawkins 2019, Putland et al. 2019, Duarte et al. 2021). Additionally, species that rely on magnetic and electric fields for foraging, communication and navigation are susceptible to the impacts of electromagnetic fields generated by subsea power cables (Gill et al. 2009, Taormina et al. 2018, Hutchison et al. 2020a). Increased artificial lighting or changes in light patterns from moving turbine blades are also reported at OSW sites (Honkanen et al. 2025), potentially affecting light sensitive species. Such changes to the sensory environment can cause behavioural changes, has the potential to disrupt migratory routes, alter detection of prey for vulnerable species and potentially aggregate some fisheries species through attraction to energy emissions (Hutchison et al. 2020b, Honkanen et al. 2025); therefore, the potential consequences for fisheries species should be determined.

Evidently, the construction and operation of OSW infrastructure will lead to alterations of the existing habitat that could impact fisheries species. These habitat changes can be grouped into three broad categories:

i) benthic species community change, in terms of epifaunal species presence, their abundance, biomass, and distribution associated with the new physical structures (hereafter shortened to ***physical benthic***);
ii) hydrodynamic changes in the water column and seabed associated with the physical structures installed (hereafter referred to as ***physical hydrodynamic***);
iii) the alteration of the ***sensory environment***, through OSW-related (pre)construction and operational energy emissions (e.g. underwater noise, electromagnetic fields and thermal) during the different phases of OSW development (Gill 2005).

The resulting environmental pressures will have different intensity, frequency and duration between (pre)construction and operational phases, which will then determine the effect on fisheries species. Using the three main habitat change categories, our study used expert elicitation and evidence mapping to set out how the pressures from these habitat changes associated with OSW construction and operation could lead to Cause–Effect pathways that result in impacts on fisheries species. We took a holistic approach through considering known potential pressures associated with OSW habitat change applicable to any geographic location or fisheries species. We reviewed available literature to identify direct evidence supporting elements within predicted Cause–Effect pathways, which also highlighted gaps in the evidence base. Given that the evidence base is continually growing and there may be emerging Cause–Effect pathways that were not included in our study, the goal of this study was to identify the pool of available evidence or gaps therein, rather than provide an

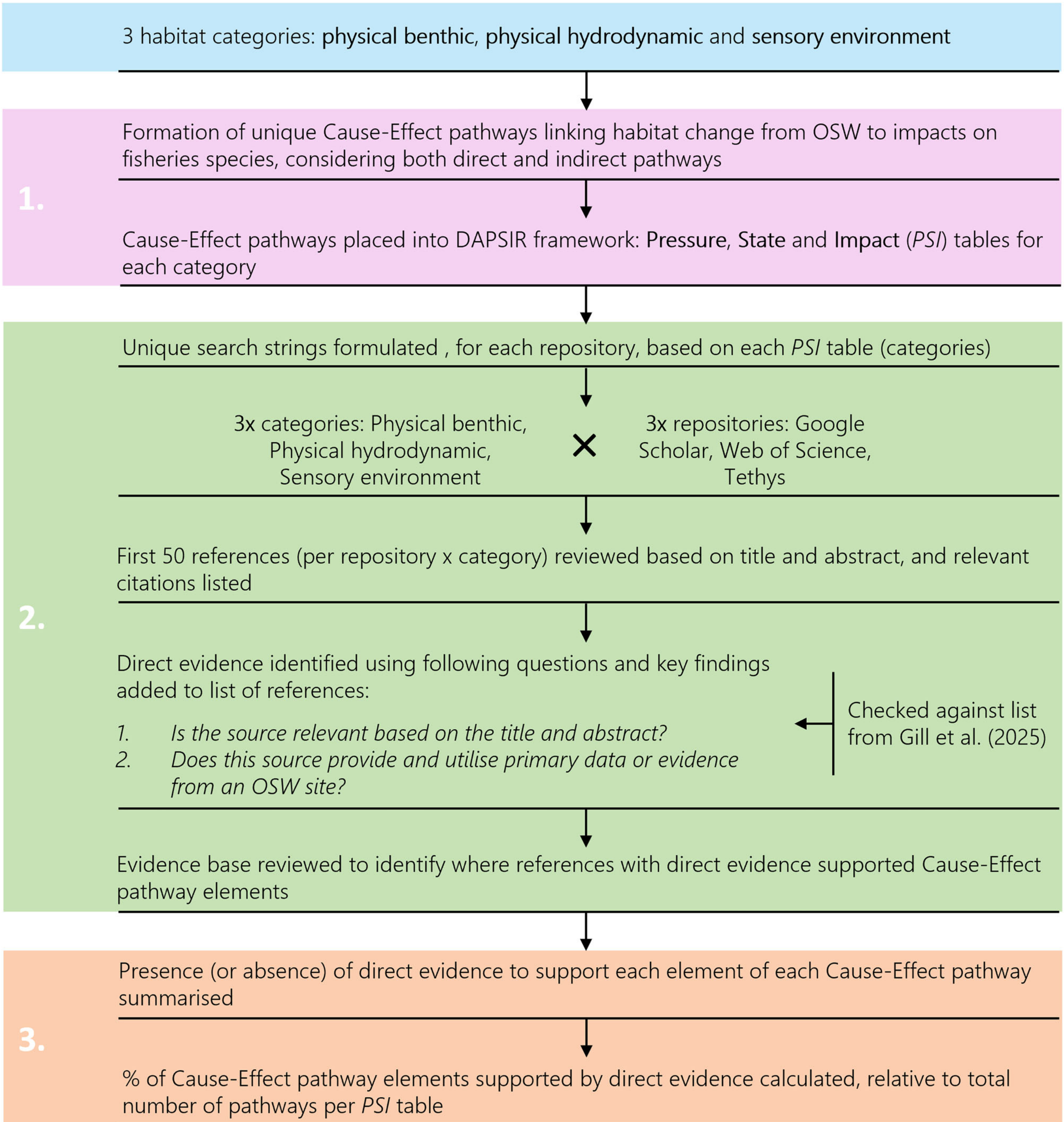

Figure 1 Schematic summarising the stages of the methodological approach used for this study, starting with the three habitat categories. The method followed three stages: Stage 1., Stage 2. and Stage 3.

exhaustive list of literature sources. Therefore, the findings of the study should be considered in this context. Closing evidence gaps remains critically important to understand impacts of OSW habitat changes on fisheries species, and to determine the potential impacts on fisheries with greater confidence.

Methods

The methodological approach followed three stages (Fig. 1):

1) Setting out of the plausible Cause–Effect pathways for the three habitat categories, linking habitat change from OSW construction and operation with predicted impacts on fisheries species, within an adapted, holistic Driver-Activity-Pressure-State-Impact-Response (DAPSIR) framework (Oesterwind et al. 2016, Elliott et al. 2017).
2) A targeted review of the literature to identify and extract evidence supporting the predicted Cause–Effect pathways.
3) Use of Cause–Effect pathways and the supporting direct evidence to identify gaps and future research needs. Where we refer to evidence gaps, this means that direct evidence was not identified through our standardized approach, where we focused on scientific peer-review documents as the primary

source of evidence. It is important to note that there may be evidence not publicly available to our targeted review of the literature.

For the purposes of this study, we defined fisheries species as any marine fish, shellfish, or cephalopod species of commercial or recreational importance. We also use the term "fish population" in a broad sense to refer to biologically defined groups of interbreeding individuals of the same species, that can be widespread (e.g. Begon et al. 2006).

The study was undertaken between 2023 and 2025 by the ICES Working Group on Offshore Wind Development and Fisheries (WGOWDF). The Working Group (WG) comprised 66 members, predominantly from the North Atlantic, Baltic and Mediterranean regions, with a wide range of expertise including fisheries scientists, social scientists, economists, marine biologists, and ecosystem scientists, from across the fishing and OSW industries, academia, government, and NGOs. A subgroup of 21 WG members contributed primarily to the review, analysis and delivery of this paper (i.e. the authors of this manuscript), hereafter referred to as we/us.

We chose not to include Floating Offshore Wind (FLOW) in the Cause–Effect pathway assessment as this is a technology still under development; nonetheless, our approach is relevant to FLOW in the context of potential impacts on fisheries species. Similarly, as very few OSW developments have been decommissioned to date, the Cause–Effect pathways of potential impacts on fisheries species relating to decommissioning were not considered further here.

DAPSIR framework approach

The *DAPSIR* framework provided an organized structure for setting out the relationships between human activity, the pressures exerted and the consequent environmental change, with considerations of the impacts on ecosystem services (e.g. fisheries) and potential management response. The established *DAPSIR* framework (Bryhn et al. 2020, OSPAR 2023) was adapted for the purpose of this study. We defined the Driver (i.e. the policy drive for renewable energy) and the Activity (i.e. offshore wind construction and operations) and applied the remainder of the modified *DAPSIR* framework to examine the relationship between OSW development (including all infrastructure associated with fixed OSW) and the associated pressures leading to marine environmental changes of relevance to fisheries species (Fig. 2; Elliott et al. 2017, Kuempel et al. 2025). Through our adapted OSW-Fisheries *DAPSIR* framework, we distinguish the main ecological system elements and the social elements whilst retaining the key linkages (Fig. 2).

The *DAPSIR* definitions we applied were adapted from Oesterwind et al. (2016), where:

- Driver (*D*): A human societal need e.g. need for renewable energy and demand for food (fishing).
- Activities (*A*): The installation and operation of an array of offshore wind turbines or fishing activity.
- Pressure (*P*): The response to driver/demand, an action or feature that exerts change in the natural/baseline environment e.g. introduction of turbine structure.
- State (*S*): The condition of the ecological element of relevance, including biotic and abiotic characteristics. The receptor of effects/impacts of the pressure e.g. habitat change.
- Impact (*I*): The consequences of (environmental/ecological) state change and the (positive/negative/neutral) environmental (and socio-economic) effects of such change. Whilst the impacts on humans (*I*) are the traditional focus of the *DAPSIR* framework we specifically applied it in the context of the change to fisheries mapped back to the specific changes to the fisheries species.
- Response (*R*): Management actions aimed at prevention, mitigation, restoration or adaptation to changes influenced by the Driver through the Pressure, State and Impacts relationship.

Stage 1: identification of plausible Cause–Effect pathways, linking habitat change from osw construction, and operation to predicted impacts on fisheries species

Application of the modified Cause–Effect pathway framework

Figure 2 shows the OSW-Fisheries system as the *DAPSIR* framework. The *D*, *A*, *R*, and *I* sit predominantly within the social part of the system, whereas the *P* and *S* mainly appear within the ecological part of the system. We identified and defined Cause–Effect pathways that linked multiple pressures, associated with habitat change, to state changes that would plausibly result in impacts of relevance to fisheries species from OSW development (Fig. 1). From there, we identified the Cause–Effect pathways associated with each of the three habitat change categories attributable to OSW development with potential to exert both direct and indirect impacts on fisheries species. The Cause–Effect pathways considered the main life stages (egg/embryo development, larval, juvenile, and adult), all geographic regions and fisheries species. The broader social and economic impacts on fishers and fleets were not addressed, as they were beyond the scope of this study. However, we recognize that they are central to the social parts of the system (Fig. 2), which together with the ecological parts will determine the impact of OSW on fisheries.

To clearly determine how the Pressure (*P*) and State (*S*) changes lead to Impact (*I*), we identified two important sub-elements of *I*, namely Ecological Impact (I_e) and Population Impact (I_p) (Fig. 2). Ecological Impact represents the end point of the state change arising from a Cause–Effect pathway. An I_e will only be realized as an impact on the fishery if it is significant at the population level, i.e. through alterations to species abundance, biomass and distribution impacting more than just a few individual fish. The I_p sub-element links the outcomes of the Cause–Effect pathways within the ecological system through to the (human) impact (*I*) on the fishers, within the social system (Fig. 2). The distinction between I_e, I_p and *I* can enable management and/or policy response (*R*) direct towards either the social or the ecological parts of the system or multiple points (white broken arrows, Fig. 2).

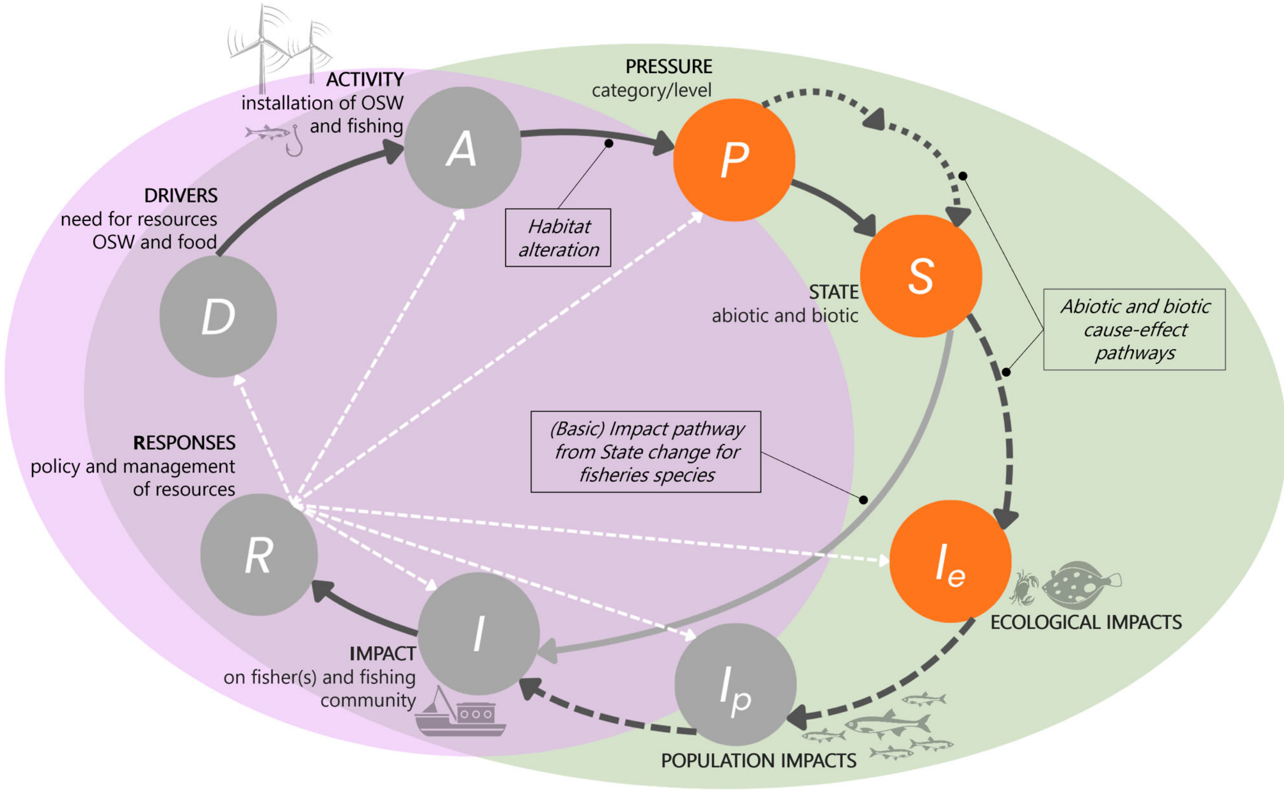

Figure 2 Depiction of the OSW adapted *DAPSIR* framework applied in the present study showing where the elements belong within the ecological (represented by the green shading) and social (represented by the purple shading) parts of the system. Each element, namely Driver (*D*), Activity (*A*), Pressure (*P*), State (*S*), Impact (*I*), and Response (*R*) is shown with text to highlight the associated key aspects. Orange circles identify the *PSI* elements which are the focus of this study. The links between each element are shown by arrows. The solid black and grey arrows represent the traditional *DAPSIR* linkage. The dotted black arrows indicate that the pressure to state change may take more than one step and can be made up of multiple potential abiotic and biotic Cause–Effect pathways relating to the fisheries species. The dashed black arrows highlight the separation, of the impact on fisheries species, into two sub-elements: ecological impact (I_e) and impact on the fisheries species population (I_p), which must be considered to determine the social and/or economic impact (*I*) on the humans. The white broken arrows between *R* and other elements of the system represent options where active management responses could be considered. Image credits of vector icons: wind turbines by Freepick, other objects and marine creatures by Vecteezy.

Within the ecological system, the Cause–Effect pathways that link the state change to the I_e could be either abiotic or biotic, or both (Fig. 2). Furthermore, a pathway could be direct (e.g. the movement of cod away from OSW pile driving during construction) or indirect (e.g. association of prey species with the turbine foundations leading to attraction of predators, such as mackerel).

Pressure-state-impact (PSI) tables

To examine how fisheries species could be affected by OSW habitat change we focused on the impact sub-element of I_e within the modified *DAPSIR* framework, primarily at the local or individual level. This is owing to the limited evidence base linking OSW development and fisheries population level impacts, which was highlighted by the systematic review of Gill et al. (2025). We formulated Pressure-State-Impact (hereafter *PSI*) tables and used those to identify Cause–Effect pathways that could lead to impact on the fisheries species, at an individual level (Supplementary material; Table S1, Table S2, Table S3). WG members brainstormed, discussed and then listed out potential pressures for each habitat change category (e.g. *sensory environment*). From each pressure, the WG members considered plausible associated abiotic and biotic state change(s) and the resulting I_e.

Three *PSI* tables were formulated, one for each of the three key habitat change categories: *physical benthic*, *physical hydrodynamic*, or the *sensory environment*. Within the *PSI* tables each row represents a unique plausible Cause–Effect pathway relevant to the habitat change category (Table S1, Table S2, Table S3). Each Cause–Effect pathway identifies the type of species habitats considered: pelagic or demersal/benthic and life history stage. Furthermore, each pathway within the tables distinguished between abiotic or biotic state changes in the environment.

The aim was to provide an holistic overview, capturing the key pressures, state changes, and impacts on fisheries species, rather than including exhaustive details of all possible pressures, changes and impacts. Upon completion, each *PSI* table was reviewed by an independent expert, from within and outside the WG, with specialisms on either the *physical benthic*, *physical hydrodynamic*, or *sensory environment*.

Finally, it is important to note that although we did not consider the magnitude or scale of the I_e, we acknowledge that the scale of local and individual impacts on species and habitats will strongly determine the consequential impact on fisheries species at the population level.

Stage 2: Review of the literature with the specific objective of identifying where direct evidence exists to support the predicted Cause–Effect pathways

Once the Cause–Effect pathways were organized into the *PSI* tables a targeted review of the literature was undertaken to identify where there was at least one source of direct evidence to support the statements in the predicted pathways. Direct evidence was defined as empirical evidence with data sources direct from OSW sites or experimental studies with conditions designed to mimic those at OSW sites. Data and evidence from other human impacts e.g. oil and gas, or regions without OSW developments, were not considered, as whilst they represent potential sources of related evidence that could help with some knowledge gaps the direct comparison is subject to debate. Similarly, modelling studies were not considered direct evidence for the purpose of this study. We acknowledge that modelling is critical to forwarding the science on this topic, particularly with regards to understanding the wider consequence to the fishery. Our focus was to identify direct evidence from OSW studies that supported the predicted Cause–Effect pathways and effects on fisheries species, rather than undertake an exhaustive synthesis of the literature and data on OSW or related effects. Furthermore, rigorous models require validation with empirical data, hence the importance of identifying where direct, preferably *in situ*, data are lacking. Therefore, where we refer to “lack of evidence” in our study, we mean at the time of the review Cause–Effect pathways were not supported by publicly available data from OSW sites or studies designed to reproduce OSW conditions.

To identify the relevant literature (peer-reviewed journal articles, publicly available reports, PhD theses), three different repositories were used (Fig. 1): the academic database Web of Science for journal published material; the general search engine Google scholar; and Tethys a website that compiles metadata and links on offshore and marine renewable energy material and research programmes. The *PSI* tables were used to identify the key words on the pressures, states and impacts relevant to each of the three categories: *physical benthic*, *physical hydrodynamics*, and *sensory environment*. These key words were used to formulate clear and unambiguous search strings, encapsulating both the habitat-related change and the impact on fisheries species. Various combinations of search strings were trialled, testing how number of words, detail of vocabulary, and specific terminology, impacted the number of outputs and the relevance of the outputs. Each repository and each of the three *PSI* table categories, had unique search strings that were input into each of the three databases (Supplementary table; Table S4). The literature search was not limited by geographic location, or fish species or year of publication. However, all literature searches were completed by December 2024. Any studies published after this date were not included in the literature pool used to identify direct evidence for the *PSI* tables but some are considered in the discussion of the paper. Although a structured method was followed for the assessment of the literature and evidence base, this was not a comprehensive or systematic review: our aim was to find at least one record, or else conclude there were no records, within the literature searched.

For each of the search strings of the three pressure categories, we examined the first 50 literature sources returned by each search engine. The returns were based on relevance to the search strings determined by the search engine. Only the first 50 sources from each repository and for each *PSI* category were considered as beyond those initial 50, the relevance of the key words in the title and abstract of the sources notably decreased. Next, we reviewed literature sources for relevance to the topic based on the title and abstract, noting that in some cases there were less than 50 outputs to review. Any sources deemed relevant were recorded by their citation in a list. This reference list was cross referenced with a recently published systematic literature review on the topic of fisheries species and OSW by Gill et al. (2025), to ensure that no key research was omitted. Any new and relevant sources, identified in the literature search and from the literature summary were compiled. A phased approach was then used to identify those relevant studies, reports and papers that provided direct evidence (Fig. 1). For each source we addressed a list of questions and summarized information:

- Is the source relevant based on the title and abstract?
- How is this source relevant?
- Does this source provide and utilize primary data or evidence (e.g. empirical data)?
- What are the key findings of the source?

All sources identified as relevant and providing direct evidence were compiled into a final literature summary table (Fig. 1). Next, we scrutinized each *PSI* table and Cause–Effect pathway within to identify any direct evidence supporting each element (pressure, abiotic, and/or biotic state change and ecological impact statement) in that pathway. Where a reference was deemed to provide direct evidence for a statement it was added to the relevant reference column in that *PSI* table. Only literature that was considered direct evidence was incorporated into the *PSI* tables as references/supporting evidence for the tables.

Stage 3: using the assessment of the Cause–Effect pathways to identify evidence gaps and therefore target future research needs.

Once the summary of the literature identified as relevant had been added to the *PSI* table for each habitat change category, we considered each Cause–Effect pathway and characterized the direct evidence base for every element of the pathway as follows: a) no evidence; b) evidence related to the Pressure; c) evidence related to the Pressure-State relationship; d) evidence related to the Pressure-State-Impact relationship. No direct evidence signified that at the time of our review there was no literature source found containing evidence to support that element of the predicted Cause–Effect pathway. For each *PSI* table (habitat change category) we calculated the percentage of Cause–Effect pathways with direct evidence to support each *PSI* element, relative to the total number of pathways. In some cases, more than one source provided direct evidence for a single element, however each element was counted only once and therefore proportions were not weighted. By organizing the information in this way our study highlights where the evidence base does/does not link one *PSI* el-

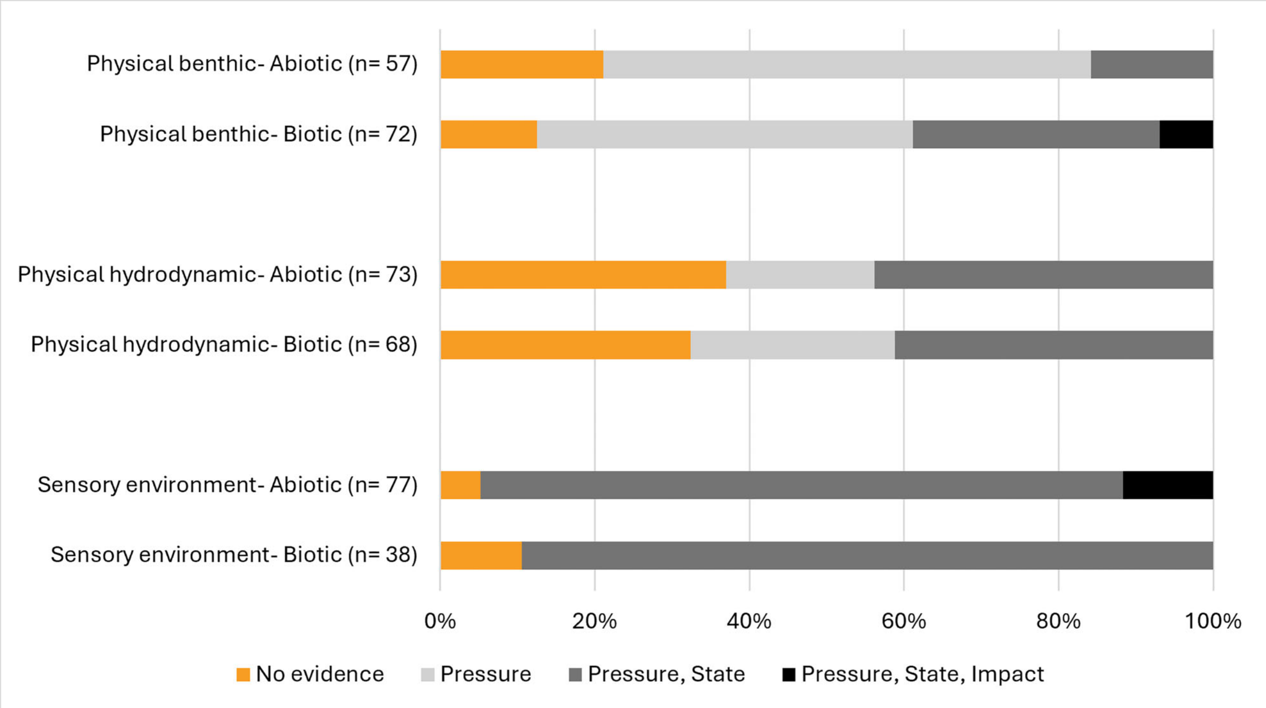

Figure 3 A summary of the patterns in the evidence base for the Cause–Effect pathways within the *PSI* tables. The number of individual Cause–Effect pathways identified within each habitat change category is represented by "n," split by whether those pathways referred to abiotic or biotic state changes. Shading indicates the proportion of Cause–Effect pathways within that habitat change category and where there was direct evidence to support each element of the pathways. (Table S1, Table S2, Table S3).

ement to the next element of the adapted *DAPSIR* framework. It should be noted that the pathways were not weighted, not independent and that the quality of the evidence was not assessed.

A proportion of literature sources provided direct evidence of localized changes to fisheries species, e.g. changes in abundance or distribution, and hypothesized the causes for such changes, but did not provide direct evidence linking the pressure to the impact recorded (e.g. Bergström et al. 2013). These sources could not therefore be linked to the Cause–Effect pathways, as they focussed only on the impact element and provided no evidence of the cause of the change, hence were not recorded in the *PSI* tables. This body of research was still considered in the discussion as it provided useful context.

Results

The results reflect the overarching patterns set out in stage 1 and evidenced from the completed *PSI* tables, described in stage 2, and the subsequent analysis based on stage 3 of the methods.

Summary of supporting evidence

Overall, 385 plausible Cause–Effect pathways of relevance to OSW-fisheries interactions across the three categories of habitat change were identified. This list of pathways included the key pressures, abiotic and biotic state changes, and the consequential impacts associated with habitat change attributable to OSW development on fisheries species.

In general, the analysis revealed a consistent pattern across *PSI* tables indicating where the research has focussed within the *PSI* framework (Fig. 3). For many pathways, there was direct evidence of pressures leading to a state change, however the link between state changes and impacts on fisheries species was rarely evidenced. For all three categories of habitat change (*physical benthic*, *physical hydrodynamic*, and *sensory environment*), including both biotic and abiotic pathways, there were some proposed pathways without any direct evidence identified to support any element within that pathway (Fig. 3). The review also showed that studies on environmental effects of OSW development often focus either on the state change in the environment, without the link to the impact on fish, or on alterations to fish abundance or biomass in response to the presence of OSW, but without providing evidence of the cause of change (Fig. 3). These studies therefore could not be linked to a specific Cause–Effect pathway, as the impact was not linked to the pressure or state change, and were therefore not recorded into the tables. Very few studies provided evidence for the entire Cause–Effect pathway, that is, from the exertion of an OSW-related pressure and the subsequent change of state in the habitat of a fisheries species, to the impact on the fisheries species (black shading, Fig. 3).

Physical benthic environment

With regards to the benthic environment, there were 129 predicted pathways identified, of which 72 considered biotic factors and 57 considered abiotic factors. Some pathways associated with the benthic environment had no evidence to support any of the *PSI* elements (abiotic pathways = 21%, biotic pathways = 13%; Fig. 3). Most of the pathways had direct evidence only supporting the pressure statements (abiotic pathways = 63%, biotic pathways = 49%). For biotic pathways 7% of plausible pathways had direct evidence to support the whole *PSI* pathway (Fig. 3).

Abiotic and biotic pathways showed similar patterns with regards to research focus. There was little direct evidence of change during the construction phase, e.g. evidence of sediment resuspension and deposition. Meanwhile, there were multiple studies providing direct evidence of the colonization of hard structures during the operational phase (e.g. Birklund and Petersen 2004, Bunker 2004, Langhamer and Wilhelmsson 2009, Andersson and Öhman 2010), and linking the presence of hard structures to localized changes in some species distribution and feeding activities (Buyse et al. 2023a, 2023b).

Physical hydrodynamic environment

A total of 141 plausible pathways associated with hydrodynamic changes were identified, consisting of 73 abiotic and 68 biotic pathways. Of the 141 pathways none had direct evidence to support the entire predicted *PSI* pathway. A significant proportion of the pathways had no direct evidence to support any of the *PSI* elements (abiotic pathways = 37%, biotic pathways = 32%; Fig. 3). Studies utilizing empirical data, field studies or laboratory experiments provided direct evidence of hydrodynamic changes, wind wake effects, scour and turbulent wakes (e.g. Burchard et al. 2008, Whitehouse et al. 2008, Schultze et al. 2020, Floeter et al. 2022) (Fig. 3). However, there was no direct evidence demonstrating that altered water movement affected fisheries species e.g. sediment resuspension causing the clogging of gills of certain species. There was an absence of studies, providing quantitative direct evidence, linking physical changes in hydrodynamics to the consequential ecological impacts.

Sensory environment

Research on the *sensory environment* included 115 pathways, of which 77 considered abiotic factors and 38 considered biotic factors. In most cases, direct evidence only supported pressure and state change statements (abiotic pathways = 83%, biotic pathways = 89%). Just 11% of abiotic pathways, and no biotic pathways, had direct empirical evidence to support the entire *PSI* pathway. Whilst 5% of abiotic and 11% of biotic pathways had no direct evidence to support the predicted pathways at the time of the literature review (Fig. 3).

Studies on the *sensory environment* considered sound pressure and sound particle motion created by both installation and operation of turbines (Amaral et al. 2018, Sigray et al. 2022). Changes in particle motion and sound pressure, associated with OSW turbine installation, were demonstrated to impact fishes by altering swimming behaviour (Cresci et al. 2023), movement away from or avoidance of the sound source (Hawkins and Popper 2014), physiological stress (Bruintjes et al. 2017), and behavioural changes that affected antipredator behaviours (Everley et al. 2016). It should be noted that many of these studies were based on experiments that aimed to reproduce OSW conditions but were conducted in different environments.

Figure 4 provides selected examples of Cause–Effect pathways, to illustrate how we determined where there was direct evidence to support the different elements. Example 1 in Fig. 4 outlines an expected pathway associated with siltation and smothering. In this context, siltation relates to the accumulation of finer sediment in water bodies, whilst smothering links to the damage caused to habitats or organisms because of deposited sediments (Jones et al. 2019). Although siltation and smothering are commonly referred to as impacts associated with the pile driving of turbines (Hiscock et al. 2002), at the time of the literature review there was no literature providing direct evidence or data supporting the statement in example 1.

Example 2 in Fig. 4 predicts that the presence of a turbine in the water column would increase turbidity and light attenuation. As less light reaches deeper into the water column, the poor visibility can affect local predator-prey interactions, e.g. leading to alteration of feeding behaviours of species. Direct evidence was only found to support the pressure statement (Vanhellemont and Ruddick 2014). Although there is evidence that increased suspended particle matter reduces light penetration in the water column (as demonstrated by Devlin et al. 2008), the literature review did not find any direct empirical evidence of this effect at an OSW site. Hence, no direct evidence supported this state change statement in the *PSI* tables.

Example 3 in Fig. 4 outlines a pathway detailing how expected sound attributable to either construction or operation of turbines creates water particle motion and sound pressure changes that could lead to mortality of some prey species, increase competition for remaining prey, or cause movement away from the area. There is direct evidence of changes in sound pressure and particle motion (Andersson 2011, Amaral et al. 2018, Sigray et al. 2022), but a lack of evidence of species mortality of those species, increased competition or species redistribution.

Example 4 in Fig. 4 shows a pathway supported by several studies within Belgian OSW sites. The direct evidence from these studies exemplifies how the addition of new hard substrate within the water column increases habitat complexity and prey availability, which in turn alters the spatial distribution and movement patterns of plaice *(Pleuronectes platessa)* through attraction, ultimately leading to changes in their diet (Buyse et al. 2022, 2023a, 2023b).

Discussion

Setting out the OSW-fisheries system within the adapted *DAPSIR* framework and the subsequent formulation of the *PSI* tables with the supporting literature was an effective approach. Using the framework, we were able to map the evidence base relating to the pressures and state changes associated with habitat changes attributable to OSW development and the potential impacts on fisheries species. Whilst there was evidence of pressures associated with OSW habitat change, the analysis of the associated Cause–Effect pathways, highlighted the lack of evidence linking abiotic state changes to the subsequent biotic state change. Similarly, very few pathways had evidence to support the entire Cause–Effect pathway. Ultimately, these limitations in the evidence base hamper our ability to link the habitat change resulting from OSW construction or operation to the ecological impacts (I_e) on fisheries species across their life history, which could then translate into population impacts (I_p). This limited understanding of the ecological impacts on fisheries species, and our ability to predict broader scale impacts on populations also limits our determination of consequences to fishers and fishing communities (Gill et al. 2020, Gimpel et al. 2023, 2025).

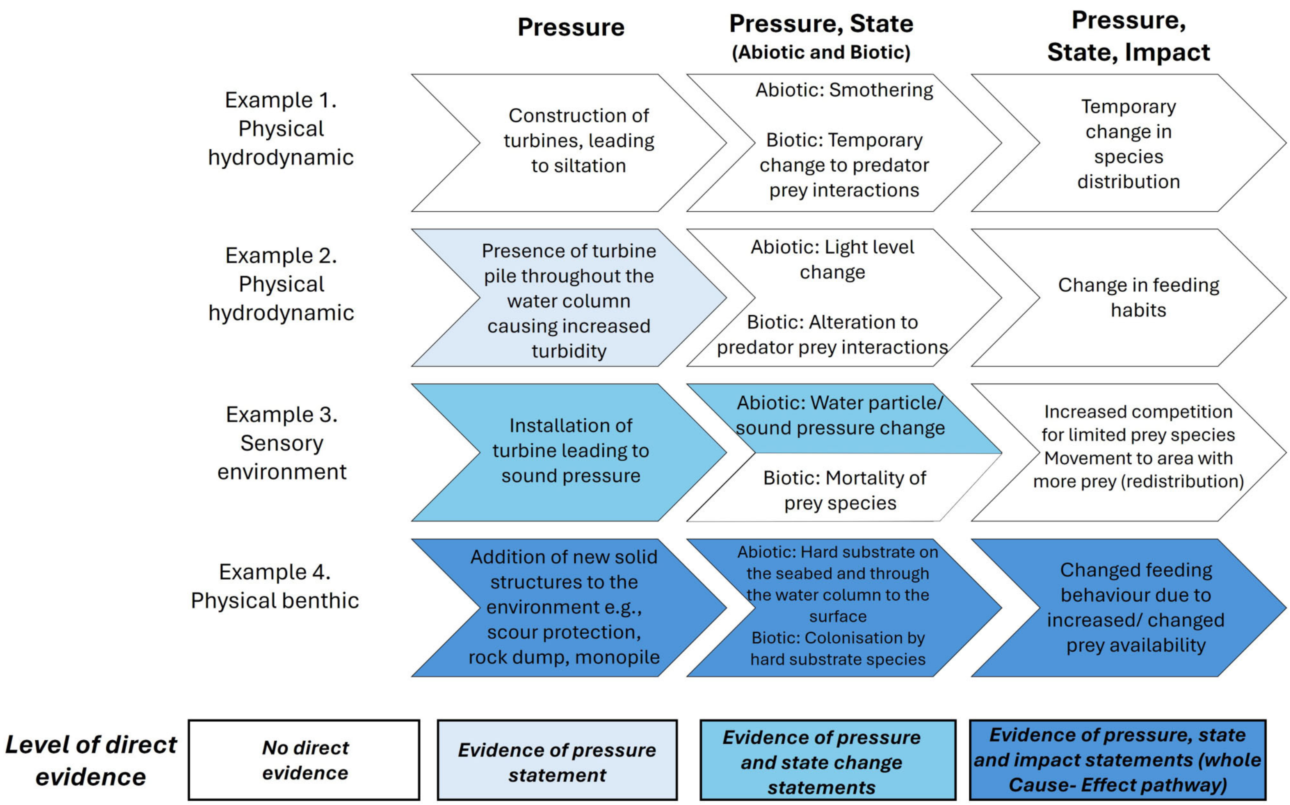

Figure 4 Example Cause–Effect pathways from the *PSI* tables illustrating elements that were supported by direct evidence and data. The colour represents where there was direct evidence supporting the statement. Example 1 - No evidence to support pathway. Example 2 - Only evidence to support the pressure element of the pathway. Example 3 - Evidence to support the pressure and abiotic state change elements of the pathway. Example 4 - Direct evidence to support the pressure, state change, and consequential impacts in this pathway (Table S1, Table S2, Table S3).

The process of setting out the Cause–Effect pathways in the *PSI* tables highlighted the habitat changes that OSW development can exert on fisheries species and showed that disentangling the effects of the different pressures and their interactions remains a major knowledge gap. It is commonly assumed that OSW sites can have a "positive" impact where fisheries species are attracted by hard structures resulting in increased occurrence and abundance, known as the "artificial reef effect." Some studies also state that OSW sites act as *de-facto* marine reserves owing to the exclusion of fishing activities (Fitkov-Norris et al. 2025). With this study, however, we argue that a holistic approach is required, as it is important to consider whether any observed changes in abundance, biomass or production of fisheries species are likely to evolve in the long-term (e.g. they may increase, decrease or the change may be negligible), which will depend on species sensitivity, and on the specific pressures and the intensity.

While our literature search and analysis intentionally focused on the OSW evidence base, the causes and potential consequences of environmental changes related to other types of marine structures have also been studied, such as oil and gas, (e.g. lighting; Barker and Cowan 2018) and intentional artificial reef construction, which have been shown to alter the density and biomass of fish (Granneman and Steele 2015). Evidence such as this could be used to develop hypotheses further and support Cause–Effect pathways related to OSW habitat change, as long as the limitations of such comparisons are taken into consideration. We focused on the evidence base (and gaps) directly attributed to OSW developments, in order to inform the scientific debate as well as management responses to the specific habitat changes associated with OSW development.

The potential population level impacts on fisheries species may arise through changes at the individual level, shown by altered length and weights at age, developmental changes through their life-history, or altered distribution and abundance of the species and their habitat association (Hogan et al. 2023). There are also potential indirect effects, such as: attraction or avoidance of predator and/or prey species to OSW areas leading to altered predator–prey interactions; potential species redistribution and spatial spillover to adjacent areas as a result of biomass increases around structures; shifts in foraging, refuge, and shelter opportunities; recruitment changes; intra- and interspecific competition; and facilitation of invasive species (e.g. Methratta 2025a, De Mesel et al. 2015, Methratta and Dardick 2019, Mavraki et al. 2021, Wilber et al. 2022). However, current limitations in OSW monitoring and data collection at the appropriate spatial and temporal scales prevents the extrapolation of these local changes on fisheries species to larger scales or population-level effects (Gill et al. 2025).

Specific evidence gaps for habitat categories

The *PSI* tables we used for expert elicitation and evidence mapping, based on literature compiled up to December 2024, included several evidence gaps in terms of OSW pressures, state changes and ecological impacts spanning the three habitat categories (*physical hydrodynamic*, *physical benthic*, and *sensory environments*). These knowledge gaps require further consideration and research to ensure that impacts on fisheries species are suitably addressed.

The empirical direct evidence necessary to characterize benthic organic and inorganic sediment processes, such as siltation, sediment resuspension or increased turbidity associated with OSW construction and its effects on fisheries species was either limited or absent. Studies associated with sediment transport are largely model based, however there is uncertainty around the accuracy of these outputs (Degraer et al. 2023). There was some evidence of suspended particulate matter plumes around turbine piles during the operational phase (Baeye and Fettweis 2015). Smothering of sessile or immobile species that occurs during construction and decommissioning activities remains an unquantified effect with little *in-situ* evidence, although these are commonly assumed ecological impacts of OSW development. Several direct evidence gaps were identified in the pressures and state changes linked to the construction phase e.g. sediment resuspension and subsequent siltation and clogging of gills of benthic species. Recent studies have shown that offshore wind farms can modify seabed mobility, sediment transport pathways and organic carbon burial to greater extents than previous predicted (Unsworth et al. 2026, Chen et al. 2026). Such evidence should be considered in the future when assessing OSW-related hydrodynamic habitat change relevant to fisheries species.

Other sources of data and information on sediment processes of relevance to fisheries species might be available where the data are collected as part of geophysical surveys by developers of marine artificial structures. For example, in the UK where sediment disturbance is a major concern for projects, developers are required to measure and monitor siltation to meet regulations, however, these data are often not publicly or readily available.

An emerging topic relates to chemical emissions from OSW developments that could have implications for fisheries species. The level of these emissions into the marine environment is currently uncertain and difficult to estimate, with several studies highlighting the need for targeted monitoring and *in-situ* data collection (Kirchgeorg et al. 2018, Ebeling et al. 2023, Hengstmann et al. 2025). According to Hengstmann et al. (2025) the concentration of contaminants from OSW developments in marine species is not yet being investigated. However, measuring the concentration of these potential contaminants in sediments and fisheries species and investigating their potential ecotoxicological risk levels, would appear necessary. Ebeling et al. (2023) explored metal emissions from galvanic anodes at OSW developments in North Sea sediments and concluded that the levels of legacy pollutants in the sampled sediments were within range for general North Sea sediments. However, while their data did not point towards accumulation in sediments, the authors emphasized that further investigation is required.

With regards to the *sensory environment*, research on the ecological impacts of energy emissions has thus far focussed primarily on underwater noise and electromagnetic fields. Little evidence is available for temperature changes. For example, there is no direct evidence on the potential effect on the water column effects associated with water-cooling emissions from high voltage direct current (HVDC) converter stations (Middleton and Barnhart 2022). However, understanding the impact of such environmental temperature fluctuations could be important when considering the responses of fisheries species. Evidence for the effects of artificial nighttime lighting used to aid vessel navigation is also missing from the OSW literature, although a general review of artificial light at night (ALAN) has highlighted that ALAN may affect fish in terms of attraction or avoidance and therefore should be taken into account for fisheries species around OSW sites (Marangoni et al. 2022).

Most of the pressures and impacts associated with OSW habitat changes and recorded in the Cause–Effect pathways, are frequently mentioned in the literature. While in some cases proxy evidence is cited in relation to other human activities or types of marine artificial structures, direct empirical evidence from OSW sites remains limited. Therefore, there is a need to either collect such evidence or demonstrate that comparative studies are transferable to the OSW situation and the consequences to fisheries species.

Gaps in knowledge were also evident for early life stages of fisheries species. To date, most research has focused on the adult stage, yet different life stages may have unique sensitivities and vulnerabilities to specific OSW pressures (Gill et al. 2020, Cresci et al. 2023). For any given species, each life stage may display different habitat and resource requirements, as well as differing vulnerability to abiotic factors like environmental conditions, and biotic factors, such as predation, which will operate over different temporal and spatial scales. Therefore, understanding Cause–Effect pathways in this context for each stage of the life history is essential for determining the full extent of impacts of OSW development on fisheries species and the potential consequences to populations.

Temporal and spatial scale context

Generally, the studies reviewed comprised evidence collected over a period of less than five years. The few long running studies of OSW development effects spanned more than 15 years and showed large variation in species responses over time. This was attributed to the ecological succession on the turbines with new effects emerging after about five years (Degraer et al. 2020a, 2020b, Jammar et al. 2025). These results underline the importance of establishing targeted and sustained data collection programmes, to provide evidence of how OSW impacts can change over time. A related challenge is that baseline pre-construction data collection is often limited to one or two years in duration or in many instances, not available. Discerning the impacts of OSW from other pressures acting on the system, such as climate change and fishing activities, requires an understanding of the temporal structure inherent to the system (Brander 2007, Jammar et al. 2025). Short study durations and limited baselines significantly constrain the assessment of this temporal variability in the ecological responses measured, and our understanding of how these patterns evolve within OSW developments.

In terms of spatial scales, the empirical evidence available was restricted to the boundaries of the OSW site and any reference areas. As data collection studies focus on specific OSW sites, this limits the understanding of the broad scale impacts of OSW beyond the perimeter of the site. Some impacts of habitat alteration attributable to the construction and operation of an OSW development can have wider downstream effects (Vandendriessche et al. 2015, Unsworth et al. 2026). The magnitude of the impacts on fisheries species will vary dependent on several factors including, but not limited to, proximity to the source of the disturbance, the pressure created, specific design factors of the OSW development and the species susceptibility. For example, the attraction of mobile fauna to OSW structures, is one of the most visible ecological responses to OSW presence, however evidence suggests it is generally confined to a radius of ∼100 m around the turbines (Bergström et al. 2013). Quantification of the impact of these pressures remains impossible without data collection at the appropriate spatial scale (Degraer et al. 2020b). Hence, considerations of the scale of the impact to fisheries species is fundamental to the design of data collection methods and the analysis of the data.

Effects are likely to vary among geographic areas, sea basins, regions, subregions, and other units of spatial organization (e.g. Horowitz et al. 2023, Bicknell et al. 2025). Geographical differences in oceanographic conditions, depth, benthic habitats, and species assemblages, among other factors, are widely recognized as important factors to consider when evaluating interactions between the marine ecosystem and anthropogenic pressures (Halpern et al. 2008). Notably, the majority of evidence regarding OSW effects come from studies within European sea basins. Extracting evidence from one area to support decision-making in another must be appropriately considered and justified.

Finally, future research that builds on the *PSI* methodology should assess the best approaches to incorporate spatial, temporal, and cumulative effects for both fixed and floating OSW.

Wider considerations of effects on fisheries species

Drivers of temporal and spatial changes in fisheries extend beyond the impacts of OSW. Regional and broadscale abiotic and biotic factors, such as fishing mortality (or indeed lower mortality due to displacement of fishing activities), as well as the natural variability of ecosystem processes and longer-term climate-induced regime shifts, are known to impact primary production and subsequently fisheries biomass, in some cases to the point of stock depletion (Bentley et al. 2020, Coleman et al. 2024, Cecapolli et al. 2025, Erzini 2005). Bio-climate models predict dramatic future shifts in marine communities mainly led by long-term warming and deoxygenation but also enhanced by extreme acute events (Brander 2007, Pinsky et al. 2020). Such changes influence fisheries species abundance, biomass and distribution, and overall ecosystem productivity (Cyr et al. 2025), regardless of OSW presence. Attributing the contribution of OSW impacts to long-term fluctuations in fisheries species therefore remains a key next step, particularly as current research focuses on quantifying localized pressures and resulting changes (Galparsoro et al. 2022, Gimpel et al. 2023).

Cumulative and in-combination impacts

From our Cause–Effect pathway assessment, the available evidence is predominantly concerned with I_e, which occurs at the local scale, such as altered fish abundances or biomass. The wider context of such changes remains understudied and therefore is insufficient for determining whether there are impacts of OSW habitat change on fisheries species populations across a region. This is especially important to determine given the projected rate of OSW expansion across coastal and offshore marine environments that coincide with important fisheries areas worldwide. Little is known about the cumulative effects from multiple OSW sites on fisheries species and their populations (ICES 2025a). The impact of OSW arrays across regions could be significant for fisheries species, through the alteration of ecosystem productivity (Daewel et al. 2022, Zampollo et al. 2025), and species distribution and connectivity (Buyse et al. 2022, Barton et al. 2025), with potential economic consequences for targeted fisheries (Scheld et al. 2022). A better understanding of these OSW-related cumulative effects on fisheries species would inform marine spatial planning and management and help mitigate adverse impacts on marine resources (White et al. 2012).

In addition to addressing the cumulative impacts of many OSW developments, the in-combination impacts of OSW with other marine stakeholders, including fishing, seabed drilling, shipping, aquaculture, and protected areas, should also be considered when looking to apportion cause and effects of OSW on fisheries species (Willsteed et al. 2018). The OSW-related Cause–Effect pathways that we have assessed within the ecological system (Fig. 2) will likely have consequence for the social system via the human impact (*I*), which represents the fishers and the fishing community in Fig. 2. These may include unintended consequence, such as behavioural changes relating to the fishers' activities or cumulative impacts deriving from other disturbances (e.g. gear conflict, spatial competition with protected areas, and impacts on protected features).

Within such a multifaceted and complex system, the consideration of cumulative and in-combination effects is increasingly relevant, but they are difficult to quantify and disentangle from each other, particularly as the effects on the physical and biological parts of the ecosystem occur over different temporal and spatial scales. To help address this challenge our *PSI* Cause–Effect pathway approach could be applied by identifying evidence-based impacts most likely related to the different human pressures. Once identified, data collection and monitoring to achieve the required evidence base can promoted to be implemented at the appropriate scales that can then be fully integrated into existing fisheries and environmental monitoring. (Methratta et al. 2023, ICES 2025b).

Limitations

Mapping the Cause–Effect pathways into *PSI* tables was a highly informative approach; however, we recognize some limitations. To support our overarching research question of the impacts of habitat change associated with OSW construction and operation, we chose to incorporate the evidence for each pathway at a broad scale in our *PSI* tables. Whilst this was appropriate for setting out generic pathways, future assessments could be framed more explicitly to include particular pressures and response pathways which address issues that are specific to a fisheries species.

We conducted an expert elicitation and evidence mapping study, rather than a comprehensive review of all existing literature associated with each individual Cause–Effect pathway. In that sense, we specifically identified representative studies that provided evidence for the Cause–Effect pathways. In addition, we did not weigh the magnitude, directionality, or quality of the evidence based on the methodology, duration, statistical power, or other criteria. While this information can be useful, it was beyond the scope of this paper which focused on understanding which predicted Cause–Effect pathways were supported by evidence and where gaps remain.

The development of the *PSI* tables was a time-consuming process that required contributions from ICES WGOWDF members with various expertise. Hence, the *PSI* tables were compiled by a collective of experts, and while we are confident that the key pathways have been captured, we also recognize that different experts might have been able to identify additional or more specific pathways. While the assessment of proportions of direct evidence within each Cause–Effect pathway revealed limitations in the knowledge base, published literature on the topic continues to grow and the proportion of evidence may also vary depending on the definition of "direct evidence." For example, modelling and simulation studies were not included, yet we acknowledge they are important to understand the hydrodynamic environmental changes and the ecosystem-level outcomes of OSW. Lastly, the number of pathways set out in the *PSI* tables did not reflect the magnitude of the pressure, state change or impact, although that could be an option for future development of the approach we have taken.

Future considerations

Our work has highlighted where there is current evidence-based knowledge as well as key knowledge gaps in our understanding of the impacts attributable to habitat changes (specifically the *physical benthic*, *physical hydrodynamic*, and *sensory environments*) associated with OSW development on fisheries species. Based on our assessment we propose the following recommendations:

1) Advance research targeted at scaling up from localized effects on fisheries species to broader spatial scale impacts on fisheries populations.
2) Continue to build the knowledge base for Cause–Effect relationships, particularly to close gaps between I_e and I_p and thereby improve confidence in the evidence base.
3) Aim to better connect the Cause–Effect pathways to effects on fisheries related parameters and vital population rates (i.e. reproduction, recruitment, mortality, production).

The importance of data and modelling

In addition to the specific recommendations above, we emphasise that it will be essential in the future to consider the data required and their qualities mapped across the adapted DAPSIR framework to determine the impacts of OSW habitat change on fisheries species.

To meet this requirement, data collection methods should be applied in a standardized way, including routine reporting of metrics of effects (e.g. statistical effect sizes; Methratta et al. 2023, ICES 2025b, Methratta 2025b). Data should not only be collected within the boundaries of an OSW site but also the surrounding area. Currently, where monitoring within an OSW site has been conducted, it is frequently short-term and incompatible with existing fishery surveys (Methratta et al. 2023). Fishery independent surveys have been precluded from sampling within OSW sites, as a result of turbine layouts and safety restrictions (Lipsky et al. 2025). To maintain continuity of data collection through time, and to ensure there are background data suitable for discerning broader changes and influences on fisheries species, it is important to account for the spatial coverage of other ongoing scientific surveys (ICES 2025b, 2025c). Furthermore, fishery dependent data may not be viable for detecting associated population shifts as vessels are often restricted from operating in and around OSW sites (Dunkley and Solandt 2022). Without standardized data collection, a suitable time series and alignment with wider data sources, it is difficult to confidently attribute changes in fisheries species associated with OSW (ICES 2025b). Monitoring data should be easily accessible for inclusion in fisheries species and population analyses.

Through our WG discussions, it became apparent that the identification of evidence gaps in the *PSI* tables does not necessarily mean that data must be collected. For example, the lack of direct evidence of sediment resuspension and deposition during construction does not mean data are required. It can be assumed that pile driving during construction disrupts sediment and the seabed and data are not needed to confirm this, otherwise it just adds to the issue of the DRIP (Data Rich Information Poor, *sensu* Wilding et al. 2017). Therefore, we do not recommend using the *PSI* tables and Cause–Effect pathways to justify doing science of low value, instead we recommend using them to identify evidence gaps appropriate to understanding impacts on fisheries species and to help to prioritize necessary research.

Our study intentionally focussed on evidence related to fixed OSW. However, with the emergence of FLOW and the associated complex and dynamic mooring systems and structures, there is a need to collect data to address specific knowledge gaps on how they may impact the fisheries species, which may be different to fixed turbines (Umoh et al. 2024). We recommend that appropriate baseline data be collected and subsequent targeted monitoring be conducted for FLOW sites at the earliest possible stage as part of their planning. In terms of the Cause–Effect pathways assessment, it is expected that some will be similar to those of fixed OSW, and some will be unique to the floating infrastructure and the deeper waters, where they are proposed to be deployed.

Whilst we chose to focus on direct empirical evidence, we recognize that modelling approaches have a role in predicting the outcome of OSW habitat changes on fisheries species, particularly for upscaling and simulation of effects across broader spatial and temporal scales. The dynamic and variable nature of the marine environment must be factored in when detecting and quantifying the anthropogenic impacts of OSW on the environment and fisheries species (Degraer et al. 2010). Modelling is also central in developing the understanding of hydrodynamic changes and the ecosystem-level outcomes of OSW alongside climate change effects on fisheries, and as a part of assessing the impacts on ecosystem services (Halouani et al. 2020, Nogues et al. 2021). Empirical evidence is critical to parameterize, train and validate such models, however, often it is difficult to obtain data, or the effect size is too small and is masked by a combination of ecosystem variability and sampling variance (Rose 2000). Long-time series data are essential to assess changes beyond seasonal variations and interannual variability. Furthermore, advanced spatially explicit population modelling approaches that are able to incorporate spatial variability of fisheries species vital rates (e.g. Anderson et al. 2013, Stock and Miller 2021, Lindegren et al. 2022) will provide a practical linkage between field observations and the assessment of population impacts. The integration of empirical data collection and computational modelling will likely afford a more comprehensive understanding of OSW development effects on marine fisheries species populations.

Finally, future work should account for the linkages between the ecological system, which was the focus of this study, and the social system, through appropriate data collection and analysis, particularly in relation to ecosystem services provided by fisheries and OSW (e.g. Baulaz et al. 2023). The management responses (indicated in Fig. 2) should be aimed towards minimizing or mitigating negative human impacts on the food resource provision from fisheries while optimizing any potential positive impacts of OSW on fisheries species; acknowledging that the evidence for the direction of impacts is currently equivocal (Gill et al. 2025). Studies will need to be robustly designed to incorporate the pressure(s), the receptor response and the I_e and I_p, so that outcomes can be determined with more confidence.

Conclusions

Through the adaptation of the *DAPSIR* framework to focus on the ecological aspects associated with the OSW-Fisheries species interaction, we were able to define multiple Cause–Effect pathways that may result in ecological impacts to fisheries species. Currently, the literature and evidence base does not adequately explain the links between the habitat changes associated with OSW infrastructure and the ecological impacts on fisheries species. This gap in understanding reduces the capacity of scientists to predict how these localized changes might permeate throughout to the broader marine ecosystem and therefore the potential effects on the ecosystem service of food provisioning (i.e. fisheries). The expansion of OSW has led to multiple OSW sites across the marine environment and therefore an increase in potential impacts to fisheries species populations. However, the lack of evidence from within and around fixed OSW boundaries prevents confident predictions of population level or cumulative effects on fisheries species. Similarly, the planned increase in FLOW urgently requires that we develop our understanding of potential impacts on fisheries species with regards to this technology. This calls for scientifically robust monitoring strategies that target the evidence necessary to substantiate Cause–Effect pathways linking the response of fisheries species to FLOW habitat changes.

The interaction of OSW structures with the environment is complex and multifaceted. However, it is crucial that the ecological impacts of OSW on fisheries species are better evidenced so that the population level impacts can be assessed and predicted with more confidence and any limiting factors can be identified and managed. The determination of where there is evidence and where there is not, is important to meet the aspiration of sustainable coexistence of OSW and fisheries within the marine environment. Our study provides a strong foundation for clearly delineating the known evidence of direct effects and the gaps in understanding the linkages between habitat change associated with OSW developments and the impacts on fisheries species, which a crucial step in assessing how the social system elements of the whole OSW-fisheries system could be affected.

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Author contributions

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Supplementary material

Supplementary data is available at *ICES Journal of Marine Science* online.

Conflicts of interest

There are no conflicts of interest for any of the co-authors.

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Data availability

The data underlying this article are available in the article and in its online Supplementary material.

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