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Limited Evidence Base for Determining Impacts (Or Not) of Offshore Wind Energy Developments on Commercial Fisheries Species

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ABSTRACT

The coexistence between offshore wind and fisheries has raised questions about potential impacts on species that are fished. We systematically evaluated the offshore wind farm (OWF) literature for evidence of effects leading to impacts on commercial fisheries species. First, we collated evidence of environmental effects of OWFs on fisheries species and then determined whether these could be interpreted as impacts using fishery-scale and organism-scale parameters for pelagic finfish, demersal and reef-associated roundfish, demersal flatfish, elasmobranchs and shellfish. We appraised consistency and level of agreement of direct evidence and explored the body of indirect evidence. A total of 1268 documents featured evidence of OWF effects on fisheries species, with only 60 documents (274 species records) providing direct evidence. Evidence on finfish far outweighed that for shellfish. Demersal and reef-associated roundfish were the best-studied group, while elasmobranchs were poorly evidenced. Most studies considered population rather than stock parameters. There was limited evidence of impacts, owing to inconclusive results and inconsistent effects within the parameters assessed—illustrating the importance of looking across the evidence base rather than focussing on individual studies. Hence, there is currently insufficient direct evidence to confidently determine OWF impacts on fisheries species. Overwhelmingly, the evidence deals with indirect effects, although these should not be disregarded as they can highlight plausible impacts on fisheries species, which could guide research and monitoring targeted at understanding the impacts of OWF—a pressing concern given the increased policy commitment of many nations to these two marine sectors sharing marine space.

1 | Introduction

Wild capture fisheries and offshore renewable energy represent the two most widespread human activities in the world's seas (Gill et al. 2020; Methratta et al. 2020). Commercial fisheries policy and management aim to sustainably meet food security demands (McClanahan, Allison, and Cinner 2015) as alternatives to land farming counterparts (Koehn et al. 2022). At the same time, policy targets and strategies for energy security and de-carbonisation have raised the prominence of offshore wind (OSW) development for many nations. Based on the planned expansion of OSW, there will be a significant increase in the likelihood of spatial overlap and interaction with fisheries. The consequences of which will have important implications for

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planning, management, and potential resolution of conflicting activities at sea (Gray, Stromberg, and Rodmell 2016; Thébaud and Boschetti, 2024).

Within the marine space, defined fisheries areas are used by a range of different fishing vessels and gear types (Lee, South, and Jennings 2010; Stelzenmüller, Rogers, and Mills 2008), across which offshore wind farm (OWF) sites intersect, introducing presence of multiple turbines and power transmission cable routes. Such co-existence between fisheries and OSW is increasingly attracting the attention of stakeholders and raising key questions about effects and potential impacts on the fishing industry (Alexander, Meyjes, and Heymans 2016; Stelzenmüller et al. 2021). The answers to these questions of effects and impacts will be vital to determining the outcomes of co-existence between OSW and fishing.

Studies about the outcome of fishing-OSW interactions have focused mostly on better understanding fishers' concerns (see Chen et al. 2015; ten Brink and Dalton 2018), spatial overlap (see de Groot et al. 2014; De Backer et al. 2019) and displacement and redistribution of fishing fleets and the consequences to fishers' livelihoods (Gray, Stromberg, and Rodmell 2016; Roach et al. 2018). Therefore, it is generally recognised that OSW expansion will affect fishers in some capacity, with the effects on the fisheries species themselves being a key determinant (see Gill et al. 2020; Methratta 2020). For example, studies predict effects on occurrence and biomass of certain commercial species associated with OSW areas (Friedland et al. 2021, 2023). There is also specific evidence of effects, such as underwater noise on commercial species during OSW construction (Debusschere et al. 2014; Reubens, Degraer, and Vincx 2014) and artificial reef-effect of submerged structures—the most obvious example being colonisation by mussels *Mytilus* sp. and crustacea (Krone et al. 2013; Hutchison et al. 2020). However, while these studies provide useful evidence of potential changes to the abundance and occurrence of some species, to date, there is little evidence of biologically significant OSW effects on fished species at the population level or evidence of stock-level effects. Arguably, this is the type of evidence that fishers and fisheries managers require.

Assessing the available evidence and determining the outcomes of interactions between OSW and fisheries species requires objectivity, such as that of a full systematic review; however, this is a lengthy, and costly, process best suited to evaluating a large evidence base (Konno et al. 2020). Full systematic reviews are therefore not recommended in the case of emerging topics, typically lacking in published evidence (Konno et al. 2020). As the research around OSW-fisheries impacts is still relatively new and the available knowledge limited, we adapted a systematic review approach following recommendations from the Collaboration for Environmental Evidence (CEE; Pullin et al. 2018), by blending systematic review principles with information mapping and evidence narrative.

We evaluated the evidence on the interactions between OSW and commercial fishery species by applying CEE systematic searching and study selection processes. The geographical scope was global, covering OWF construction and operation phases and focusing on commercially exploited species of finfish and shellfish (i.e., harvested species of crustaceans and molluscs, including cephalopods). Here we present our findings of evidence of OSW effects on fisheries species, critically assess the understanding of such effects, and offer recommendations to address the main shortcomings in the knowledge base.

2 | Methods

The outcomes of OSW and fisheries interactions can vary according to baseline conditions and status, time lapsed before changes are observed, spatial and temporal scales, and magnitude and direction of changes. Therefore, following Boehlert and Gill (2010), we expressly make a distinction between an OSW "effect" or "impact" on fisheries species. Here we use "effect(s)" to mean change(s) associated with a fisheries species that are attributable to a defined cause-effect relationship at the individual or multiple individuals' level. Whereas by "impact(s)" we refer to changes (or effects) of a scale or magnitude that have a biological significance at the population, stock, or community level. For example, recordings of pile-driving noise in laboratory experiments show measurable behavioural and/or physiological effects on sensitive receptors; however, whether these effects have fisheries-level impacts require measurable changes in the population or stock that exceed the expected natural variability. The definitions of effect and impact, and the direction of change (positive, adverse or neutral), are set out in Table 1.

A systematic review must clearly distinguish between "effect" and "impact" in order to assess the evidence base objectively and identify where there is evidence of meaningful impacts of OWFs on fisheries species during construction through to operation. Therefore, these definitions were specifically factored into our assessment. Note that the decommissioning stage was purposefully excluded since very few OWFs have reached that stage to date.

2.1 | Literature Review

A team of four experts in fisheries, marine human activities, and policy and two senior researchers with specific expertise in fisheries and OSW assessments undertook the literature review. The team were trained on the CEE Systematic Review and Systematic Mapping Method (http://synthesistraining.github.io/) to ensure a uniform and unbiased process. In addition, a group of six industry stakeholders was consulted to review search terms and the overarching research question: "What are the effects of offshore wind construction and operation on commercial finfish and commercial shellfish stocks and fisheries?"

2.2 | The Systematic Evaluation (SE) Method

The Systematic Evaluation (SE) method refers to the blended approach adopted, which combined Systematic Review (SR) and Systematic Mapping (SM) (Pullin et al. 2018). This method retains the advantages of a SR, namely transparency, repeatability,

TABLE 1 | Definitions of terms "effect" and "impact" of OSW on fisheries species, including the direction of change. Following the distinction between those terms made by Boehlert and Gill (2010).

EFFECT: A change to, or response of, individuals of a fisheries species attributable to a defined cause	
Positive effects	
Change/response benefits fisheries species	• Commercially important bivalves colonise turbine foundations leading to increased local abundance • Finfish attracted to OWF site for feeding or shelter
Adverse effects	
Changes/responses are deleterious for fisheries species	• Displacement or avoidance behaviour of fish in response to piling noise
No effect or neutral effect	
Either no change in measurable parameters, changes are unrelated to OSW, or changes cannot be classified as "positive" or "adverse"	• No changes in fish local occurrence and/or abundance after OWF construction • Changes in prey types in stomach content in species within OWF
IMPACT: Change/effect at a level deemed to be biologically significant for fisheries populations or stocks (set against some predefined parameter or threshold)	
Positive impacts	
Change results in increased stock size and or fisheries yield	• Species distribution change leading to increased recruitment and thus stock size of a commercial species
Adverse impacts	
Change results in declining stock size and or fisheries yield	• Stocks move out due to avoidance of OWF infrastructure and activities
No impact	
No changes at the population and/or stock level	• Changes are within natural variability for stock parameters • Decreases in fisheries species landings are related to regional factors or quota changes

and objectivity, except it does not include independent review of the systematic protocol.

2.2.1 | Literature Searches

The oceanographic and ecological changes are expected to play a role in responses of fisheries species to OSW, as per the literature (Gill 2005; Inger et al. 2009; Boehlert and Gill 2010; Taormina et al. 2018; Albert et al. 2020), were specified for the construction and operation phases of OWF development (Table 2). These were used to frame a set of clear and unambiguous search terms and search strings (Table 3) to address the overarching research question. Such search terms ensured that changes significant enough to represent impacts at fisheries stock or population level (i.e., "effect" v "impact," Table 1) were found. The full strings are provided in Table S1.

The search keywords for the query string, and wildcard notations to capture word groups with a common root, were set in consultation with the stakeholder group and then adjusted following a test using 12 benchmark records representing well-known and highly cited journal articles and reports (academic publications: Barbut et al. 2020; Bergström, Sundqvist, and Bergström 2013; Raoux et al. 2017; Reubens, Degraer, and Vincx 2014; Reubens et al. 2013; Roach et al. 2018; Stenberg et al. 2015; Vandendriessche, Derweduwen, and Hostens 2015; Wilhelmsson, Malm, and Öhman 2006; non-academic publications: Gray, Stromberg, and Rodmell 2016; Hvidt et al. 2016; Winter, Aarts, and van Keeken 2010).

Searches were conducted using Web of Science, Scopus, the online repository of non-academic material WorldCat, and Google Scholar. Additional searches were made using the wind energy database Tethys (https://tethys.pnnl.gov/wind-energy). A query calibration step for each repository ensured consistency. Google Scholar wild cards produced only limited returns due to character truncation, so query strings were limited to the maximum allowable characters, which subsequently improved the consistency of the non-academic hits (see Table 3). Initial searches were conducted in 2020, with follow-up searching in 2022 and 2023.

TABLE 2 | Potential sources of effect on the environment and on the fisheries resources during construction and operation phases of fixed-foundation OWFs, relevant to nearshore and offshore marine environment (adapted from Gill 2005).

Source of Effect	Environmental changes	Changes to fisheries species
OWF construction phase		
Sediment removal or disturbance	Habitat removal Smothering of species or habitat Increased turbidity Contaminant remobilisation Decreased Oxygen availability Increased underwater noise through particle motion, pressure or vibration	Changes in diversity, abundance, distribution Other population changes (e.g., mortality) Changes to prey availability and predation Changes to production and biomass Changes to connectivity, movement, and migration of different life stages Other indirect effects (e.g., trophic cascade; competition)
Cable laying and routing Cable protection installation	Temporary disturbance to functional habitats along route	As above
Effect of structures linked to type of turbine (monopile, jacket, foundation) and scale of windfarm (number and size of turbines)	Scale of disturbance dependent on type of structures and construction operations involved (e.g., piling noise for monopile v jacket pin piling, gravity-based placement)	As above
Windfarm spatial array and number of turbines and their spacing, and number and length of cables and routing	The scale of disturbance in terms of duration time and intensity	As above
Timing of construction	Temporary disturbance	As above, plus short- or long-term changes and dynamics
OWF operation phase		
Turbine structure and/or cable vibration	Underwater noise through particle motion, pressure, or vibration in sediment/seabed	Changes in diversity, abundance, distribution Other population changes (e.g., mortality) Changes to prey availability and predation Changes to production and biomass Changes to connectivity, movement and migration of different life stages Other indirect effects (e.g., trophic cascade; competition)
Electricity transmission—dependent on current and voltage, frequency, and variability	Electromagnetic fields, with varying intensity, frequency (i.e., AC/DC) and interaction with local geomagnetic fields and water currents (i.e., total EMF environment)	As above, plus effects on attraction and avoidance behaviours
Effects linked to the presence of underwater structures, depending on types of turbines, scale of windfarm (number of turbines and spacing) and cabling array	Use of the incidental habitat for avoidance of predators Increased habitat heterogeneity (hard surface) and colonisation opportunity (prey and refuge) Artificial-reef and fishing aggregation device (FAD) effect Altered hydrodynamics, including sediment transport processes and turbidity levels Changes to primary productivity	As above, plus changes to timing and scale of effects

2.2.2 | Eligibility Screening

Eligibility criteria were defined based on environment, fishery, energy technology, and evidence types (Table 4) and were applied consistently to ensure repeatability and transparency.

Two assessors conducted a consistency test of criteria application for the first search using 15% (minimum recommended is 10%) of the search records, which resulted in a 76% agreement and a Cohens Kappa coefficient = 0.45 (this is a metric of the agreement between two assessors and takes account of chance

TABLE 3 | Search terms agreed for inclusion in search strings. Refined search terms used for Google Scholar searching shown separately.

Population	Intervention/exposure	Outcome
Primary term: fish* OR cephalopod* OR elasmobranch* OR shellfish* *Secondary term:* mollus* OR bivalve OR crustacea* OR crab OR lobster OR prawn OR shrimp squid OR cuttlefish OR octopus shark OR skate OR ray	windfarm* OR "wind farm" OR wind turbine* OR wind park *Further terms:* OR "offshore wind" OR OWF* OR windmill*	stock* OR population* OR communit* OR catch* OR landing* OR abundance OR biomass OR distribution OR recruitment OR reproduction OR spawning OR nursery OR condition OR health OR function OR traits *Further terms:* OR nursery OR reef OR behavio*
Refined search terms for Google Scholar		
fish* OR cephalopod* OR elasmobranch* OR shellfish*	Windfarm OR windfarms OR "wind farm" OR "wind turbine" OR "wind turbines" OR wind park	stock OR population OR community OR catch OT catches OR landing OR landings OR abundance OR biomass OR distribution OR recruitment OR reproduction OR spawning OR condition OR health OR function OR traits

agreement and the level of disagreement between the assigned categories Yes, Unclear and No). The areas of disagreement were attributed to the aforementioned Google Scholar truncations. Following refinement of the search strings and the criteria, the agreement increased to over 98% with a Cohen's Kappa = 0.6, demonstrating a consistent approach.

The screening process resulted in a set of 60 documents, out of the initial 9239 documents returned by the searches (Figure 1). Many studies did not pass the screening criteria because they were not considered to be "direct" evidence of OSW impacts. These sources were separately investigated to explore additional information on "indirect" or inferred effects of OWF.

The evidence within the documents ("records") categorised as direct was collated by fisheries type (pelagic finfish, demersal and reef-associated roundfish, demersal flatfish, elasmobranchs, crustaceans, and molluscs) and parameter. Metadata were recorded on the following: geographic location and time period of the study; (any) replication or randomisation; spatial or temporal replication, sub-sampling; and measurements (metrics and units).

3 | Results

3.1 | Direct Evidence

The evidence spanned publications from 2005 to 2023, and involved mostly field observations, followed by modelling studies and field experiments (Figure 2a). More than half of the sources corresponded to studies published by countries bordering the North Atlantic basin, namely Belgium, United Kingdom, The Netherlands, USA and Germany (Figure 2b).

Most studies focused on finfish, principally demersal and reef-associated roundish and demersal flatfish, followed by shellfish (Figure 3).

The direct evidence is presented in the context of its original source, without further interpretation or appraisal of the data or the conclusions. Evidence was drawn from the text of the documents as well as tables/figures where necessary. The confidence pertains to the quantity and consistency of the consolidated records for each topic and is not a statement about the quality of the individual studies or their conclusions (see definition of "confidence" in Methods). The number of records obtained for each fishery type and taxon is given in Figure 3.

The evidence extracted from each document is included in Table S2 and summarised in Table 5, aggregated by fisheries type, stock and population-level parameters and organism-level parameters. The organism-level parameters, such as diet, physiology, condition, damage and mortality, were included as they can be scaled up to stock-level with appropriate caveats.

3.1.1 | Pelagic Finfish

There was moderate confidence for pelagic finfish overall. There was little evidence of OWF impacts for either stock or population-level or individual-level parameters, with half of the 40 records describing no effects (Table 5). Only three records described positive changes and only seven described adverse effects (Table 5). The positive changes related to population parameters, with slightly larger sprat *Sprattus sprattus* and anchovy *Engraulis encrasicolus* within OWF (Hal et al. 2012) and predicted biomass increase for Atlantic mackerel *Scomber scombrus* after OWF construction (Raoux et al. 2017). The adverse changes were a mix of population effects—reduced abundance and biomass in Atlantic herring *Clupea harengus* and reduced biomass for European pilchard *Sardina pilchardus* and Atlantic horse mackerel *Trachurus trachurus* (Perrow et al. 2011; Raoux et al. 2017)—and individual-level effects on behaviour in sprat and feeding and behaviour in Atlantic mackerel (Hawkins, Roberts, and Cheesman 2014; Krägefsky 2014).

Atlantic herring and sprat were the best-evidenced pelagic species, with 10 records each, the remainder of the 11 pelagic species were included in five or fewer records each (Figure 3). There was no consistency in response across parameters for any of the pelagic species with multiple records; they presented a mix of

TABLE 4 | Screening criteria used to determine whether evidence should be retained for the review or excluded.

Topics	Included	Excluded
Energy technology	Wind energy. Components including turbines (monopile, jacket, gravity, windmill, or array), cabling and vessels. Construction, operation, maintenance, and decommissioning	Non-wind energy such as tidal, ocean current, wave, hydropower, in-stream turbines (rivers)
Aquatic environment	Marine environments (intertidal, brackish, estuary/estuarine, marine, sea, ocean)	Non-marine aquatic environments (coastal land, freshwater, lakes, rivers, canals, reservoirs)
Geography	All regions of the world	—
Fishery	Commercial fisheries including food and industrial fisheries (fishes, invertebrates, algae/plants)	Recreational fisheries
Fishery species/taxon	Species targeted by a substantive commercial fishery (determined from Fishbase/Sealifebase or supplementary sources) Grouped taxa where it is certain they are fisheries-specific (skate and ray landings).	Species not targeted by a substantive commercial fishery, non-commercial bycatch species, diadromous taxa Grouped taxa where fisheries taxa are uncertain (crab abundance from seabed cores, aggregate total catch)
Source type	Original studies (empirical or modelling) English-language	Viewpoints, editorials, commentary, reviews/systematic reviews, publicity, lobbying, presentations/slides Duplicates (appear in more than one search); duplicated data (studies published as both a report and journal article; in these cases, the peer-reviewed article was included and report rejected) Languages other than English
Research approach	Biological parameters of individual, population, or stock Formal comparison (studies comparing OWF effects using "before/after," "control/impact" or both) Empirical studies: field observations, field experiments. Construction/operation-comparable experimental parameters (sounds mimic piling or operational noise frequencies and intensities) Predictive studies: quantitative mathematical modelling on parameters of direct relevance to fishery (species landings, recruitment)	Non-biological parameters (chemical measurements, habitat type) No formal comparison (studies not comparing to before the OWF or a control/reference; reference locations are generally locations with no human-built structures but could also be other types of built structure) Empirical studies: lab experiments (do not represent field conditions). Parameters not construction/operation-comparable (noise playbacks with limited frequency coverage) Predictive studies: qualitative/conceptual modelling, hypothetical estimates using statistical extrapolation (scaling up numbers from one turbine to multiple arrays)

positive or adverse effects and/or no effects and inconclusive evidence (Table S2).

3.1.2 | Demersal and Reef-Associated Roundfish

There was sufficient evidence ($n=95$ records) to be moderately confident in the overall evidence and each parameter type for demersal and reef-associated roundfish. Two of the species were well-represented (Atlantic cod *Gadus morhua* in 22 records, whiting *Merlangius merlangus* in 14 records) (Figure 3). However, most of the species (27 of 37; Figure 3) were referred to in only one record, highlighting a general lack of information at the species level. Similarly to pelagic finfish, there were 12 positive and six adverse records but primarily no effects (43%) or inconclusive evidence (35%; Table 5). Three of the records described changes deemed inconclusive because they could not be easily classified as either positive or adverse—Atlantic cod were older and inhabited a different trophic niche outside of an OWF compared to inside (Gimpel et al. 2023) and whiting had more significant traces of copepods in their stomachs outside an OWF (Derweduwen et al. 2012).

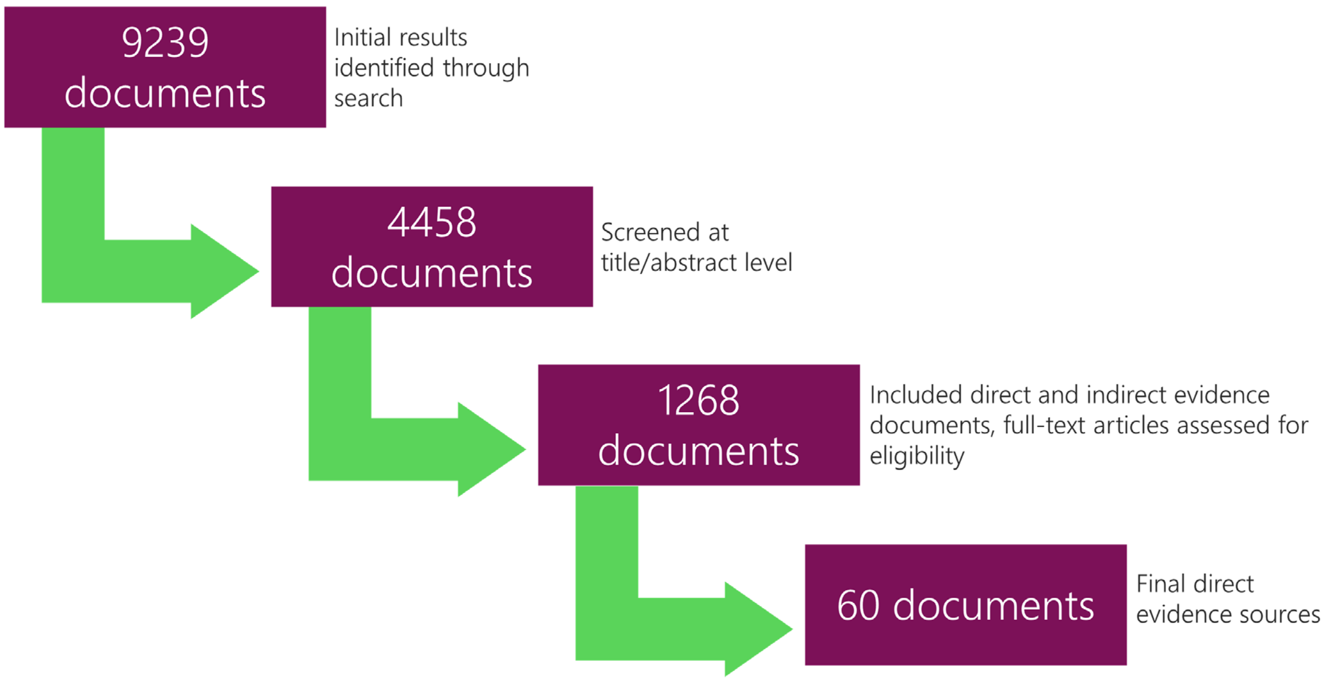

FIGURE 1 | Summary of the process of collating, sifting and identifying literature sources for the systematic evaluation.

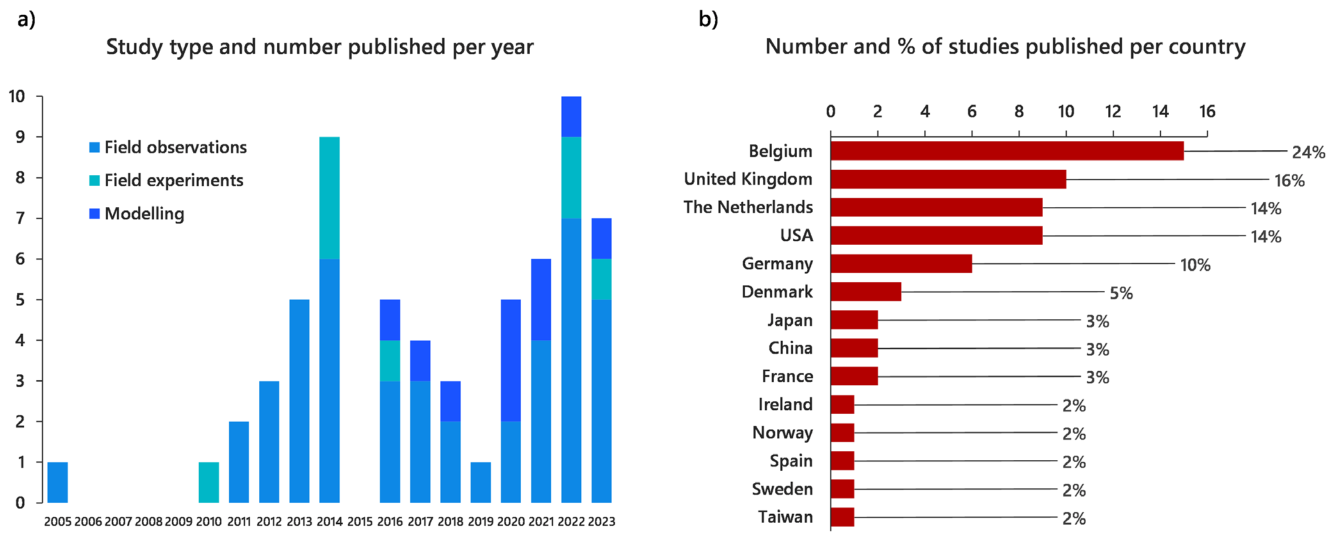

FIGURE 2 | Number and type of direct evidence studies by year of publication (a) and country of affiliation (b).

Two records of increased quantity of pouting *Trisopterus luscus* (described as higher abundance or attraction to turbines) demonstrated positive changes (Krone et al. 2013; Van Hal, Griffioen, and Van Keenen 2017). The remainder of the positive evidence was patchy. In some cases, it originated from only one record per species—cod reproduction (Gimpel et al. 2023); pouting catches, length and feeding (Reubens et al. 2013); silver hake *Merluccius bilinearis* health (Wilber et al. 2022) and black seabream *Spondyliosoma cantharus* biomass (Raoux et al. 2017). In other cases, it was inconsistent—that is, Atlantic cod with higher abundance/affinity to turbines than surrounding sands for two of the records but no effects in a third (Van Hal, Griffioen, and Van Keenen 2017; ter Hofstede et al. 2022 vs. Wright et al. 2020) and whiting with one feeding record positive and one neutral (Derweduwen et al. 2012). There was further inconsistency in the evidence around adverse effects. Three records showed behavioural changes in Atlantic cod while a further three described no effects or were inconclusive (Mueller-Blenkle et al. 2010; van der Knapp et al. 2022; Cresci et al. 2023), one whiting record described lower abundance though the other three showed no effects (Leonhard et al. 2011; Ashley 2014; Van Hal, Griffioen, and Van Keenen 2017) and one red mullet/surmullet *Mullus surmuletus* record showed lower abundance while two others showed no effects (Van Hal, Griffioen, and Van Keenen 2017; Degraer et al. 2021; ter Hofstede et al. 2022). Interestingly, while there were few records for pouting ($n=7$), 70% of them were of positive changes (higher abundances/catches, catch lengths and feeding) (Krone et al. 2013; Reubens et al. 2013; Reubens et al. 2013; Van Hal, Griffioen, and Van Keenen 2017).

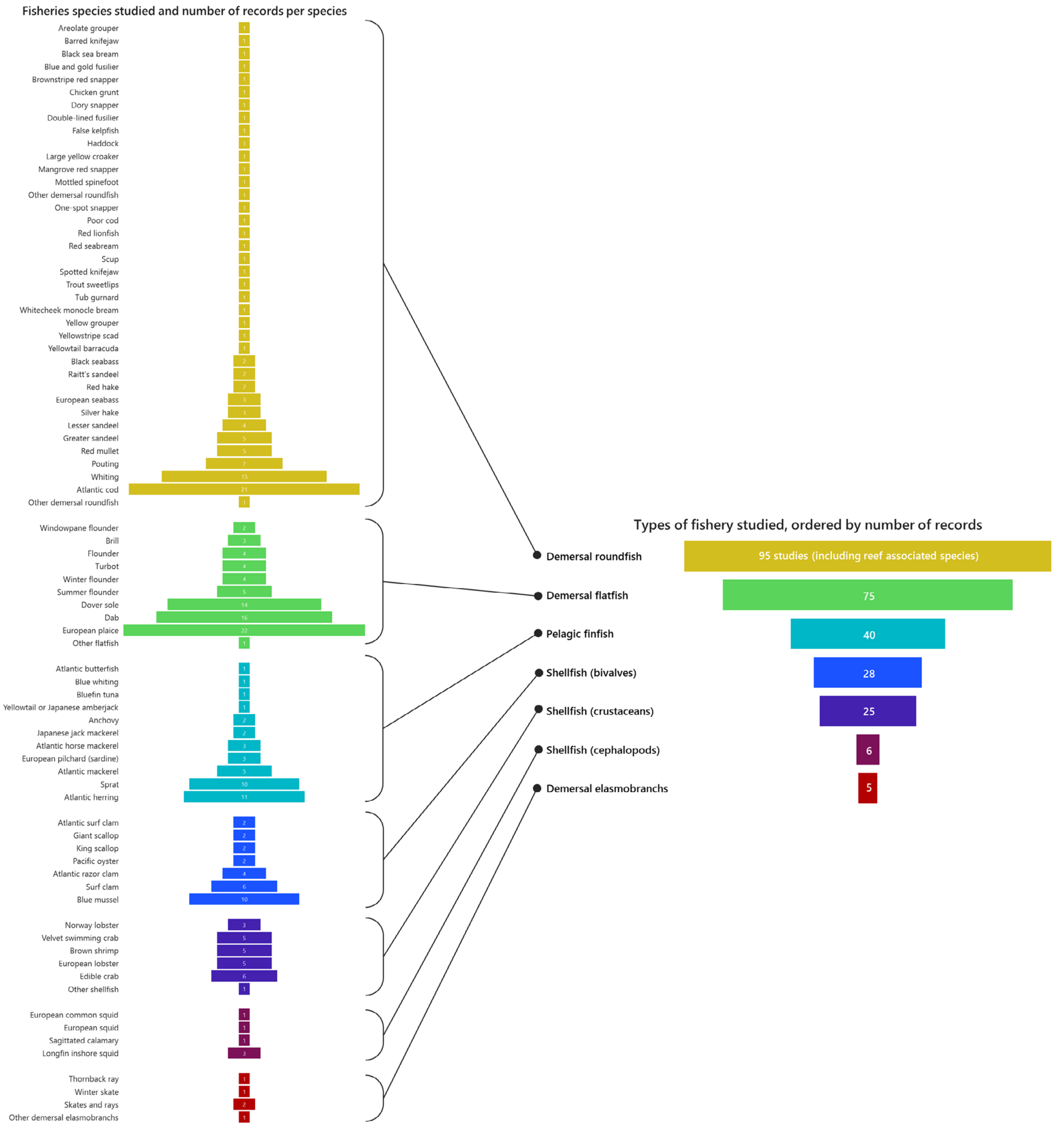

FIGURE 3 | Fishery types and species represented, showing the number of records, noting that some studies dealt with multiple types of fisheries.

3.1.3 | Demersal Flatfish

There were 75 records for demersal flatfish, which (Figure 3) concentrated on a few species, with European plaice *Pleuronectes platessa* ($n = 22$), dab *Limanda limanda* ($n = 16$) and Dover sole *Solea solea* ($n = 14$) dominating the records (Figure 3). More than half of the records were classified as no effects ($n = 39$, 52%) and, with 13 providing inconsistent results, there was little evidence of OWF effects (Table 5).

Positive changes were found only in dab and European plaice. For dab, this was represented as an increase in prey species in stomachs (Derweduwen et al. 2016), although two other records described neutral or no effects (Derweduwen et al. 2016). For European plaice, this was an increase in landings per unit effort (LPUE) (De Backer et al. 2019), biomass (Raoux et al. 2017), abundance (Buyse et al. 2022) and length (Buyse et al. 2023). The positive changes for European plaice were outnumbered by neutral or no effects for abundance

TABLE 5 | Summary of direct evidence on OWF-fisheries effects, grouped by parameter type and fishery type. The confidence rating ("high," "medium," "low") is based on the number of records and their consistency. The direction of change ("positive," "adverse," "neutral," "no effect," "inconclusive"), is also indicated. Numbers in circles represent number of records for each type of direct evidence. Blank cells represent no records.

Confidence rating	
H	High: ≥ 5 records; records provide consistent information; well-established finding
M	Moderate: ≥ 5 records; inconsistent evidence overall; differing views between studies
L	Low: < 5 records; some evidence but too few studies to resolve question
	No evidence
Direction of change	
+	Positive: Increase in a parameter or positive behavioural response
−	Adverse: Decrease in a parameter or impairment of a behavioural response
●	Neutral: Unclear whether change is positive or negative with respect to the fisheries context
✕	No effect: No change in a parameter or change cannot be attributed to OWF
?	Inconclusive: Inconclusive or ambiguous result

	Finfish				Shellfish	
	Pelagic	**Demersal round**	**Demersal flat**	**Elasmobranchs**	**Crustaceans**	**Molluscs**
Landings and commercial catches	✕ 1	✕ 5 ? 2	+ 1 ✕ 8 ? 3	✕ 1 ? 2	+ 1 − 1 ✕ 1 ? 4	✕ 1 ? 2
Quantity	+ 1 − 4 ✕ 20 ? 3	+ 7 − 3 ✕ 24 ? 27	+ 2 − 4 ● 1 ✕ 24 ? 2	✕ 2	+ 8 ✕ 3 ? 5	+ 6 − 1 ✕ 9 ? 7
Life history (age, size, reproduction)	+ 2 ✕ 1 ? 3	+ 2 ● 1 ✕ 4 ? 2	+ 1 − 6 ✕ 5 ? 6		? 2	✕ 1 ? 1
Behaviour, feeding and health	− 3 ✕ 1 ? 1	+ 3 − 3 ● 2 ✕ 8 ? 2	+ 1 − 2 ● 2 ✕ 5 ? 2			− 3 ✕ 1 ? 2
Number of records	40	95	75	5	25	34
Overall confidence	M	M	M	L	M	L

Note: None of the fishery types qualified as a "high" confidence rating for overall evidence.

(Ashley 2014; Van Hal, Griffioen, and Van Keenen 2017; Wright et al. 2020; Degraer et al. 2021; Buyse et al. 2023) and no effects/inconclusive results for length (Hal et al. 2012; Van Hal 2014).

The 12 records of adverse changes in demersal flatfish were associated with dab abundance (Leonhard et al. 2011; Van Hal, Griffioen, and Van Keenen 2017)—although three other records described no effects (Leonhard et al. 2011; Ashley 2014; Degraer et al. 2021)—and sole abundance (Van Hal, Griffioen, and Van Keenen 2017; ter Hofstede et al. 2022)—though again, no effects were described in other records (Ashley 2014; Degraer et al. 2021). Behaviour changes were reported for sole (Mueller-Blenkle et al. 2010) and predicted reproductive effects for dab, European plaice, European flounder *Platichthys flesus*, turbot *Scophthalmus maximus*, brill *Scophthalmus rhombus* and European sole (Barbut et al. 2020); one study provided inconclusive evidence of reproductive effects (no clear patterns in European plaice fecundity; Buyse et al. 2023).

3.1.4 | Elasmobranchs

The evidence base for elasmobranchs was very poor, with only five records available (Table 5). Findings were difficult to extract due to differences in species groupings. Three of the records were fishery-relevant, describing inconclusive results or no effects for landings and fishery catch per unit effort (Mueller-Blenkle et al. 2010; Ashley 2014; Hintzen et al. 2021). The two records at species level—thornback ray *Raja clavata* and winter skate *Leucoraja ocellata*—described no effects for abundance and catches, respectively (Wright et al. 2020; Gervelis et al. 2023).

3.1.5 | Crustaceans

There was a reasonable number of records for crustaceans ($n = 25$) and moderate confidence in the evidence base (Table 5). While most of the records described no effects or inconclusive results, it is notable that nine of the records described positive changes—on catch per unit effort (CPUE) and abundance of edible crab *Cancer pagurus* (Krone et al. 2013; Van Hal, Griffioen, and Van Keenen 2017; Stelzenmüller et al. 2020; ter Hofstede et al. 2022). Otherwise, records were inconclusive for crab CPUE (Stelzenmüller et al. 2020), velvet crab abundance *Necora puber* (Krone et al. 2013; Van Hal, Griffioen, and Van Keenen 2017; ter Hofstede et al. 2022) though one of the four records described no effects (Degraer et al. 2021) and European lobster *Homarus gammarus* abundance (ter Hofstede et al. 2022), as well as langoustines *Nephrops norvegicus* biomass (Alexander, Meyjes, and Heymans 2016).

3.1.6 | Molluscs

Molluscs were reasonably well represented, though with low confidence because most of the records purely related to measures of quantity (Table 5). Records mostly gave either no effects or inconclusive results ($n = 24$, 71%). Some records reported positive changes in quantity for Pacific oysters *Magellana gigas* (Wood et al. 2021) and blue mussels (recorded variously as abundance, biomass or density (De Backer and Hostens 2018; Slavik et al. 2019; Hutchison et al. 2020; ter Hofstede et al. 2022)), though blue mussel results were not consistent since other records described no effects or were inconclusive (Bech et al. 2005; Degraer et al. 2021; Causon et al. 2022). The positive effects described for surf clam *Spisula solida/solidissima* abundance were inconsistent (Bech et al. 2005; Bergman et al. 2015). There was limited evidence of adverse effects on behaviour in giant scallop *Placopecten magellanicus* (Jézéquel et al. 2022) and feeding in blue mussel (Spiga, Caldwell, and Bruintjes 2016).

There were no records of positive effects for cephalopods; two of the six records described adverse effects on abundance and behaviour in longfin shore squid *Alloteuthis subulata* (Cones et al. 2022; Guarinello and Carey 2022) and the remaining four records reported no effects.

3.2 | Indirect Evidence

Direct evidence of effects of OWFs on fisheries resource species only accounted for 6.5% of the documents returned by the searches; the remaining 93.5% represent indirect evidence. Indirect evidence is nevertheless still relevant as impacts can be inferred, and evidence came from journal papers and reviews, government reports, industry reports and technical appendices, covering laboratory, field and modelling studies, and review and opinion articles.

Indirect evidence provides important contextual and supporting knowledge and can be used to identify gaps and inform and guide further research and evidence gathering towards the determination of impacts (see Table S3, Conclusion column; also suggested by Van Hoey et al. 2021). To this end, Table S3 organises the indirect evidence into topics that align with the systematic evaluation outputs, with a summary of main effects and inferred impact relevant to each fisheries species.

While some of the indirect evidence studies appeared to address effects of OWF, further data extraction and review revealed that they were unrelated or irrelevant to the research question set out at the start of the SE (e.g., seismic underwater noise studies, or electromagnetic field (EMF) studies using non-realistic EMF intensity; Table S3).

From an ecosystem perspective, changes to the structure, function and processes of the abiotic and biotic environment are regarded as indirect, however, they remain fundamental to fisheries species and fishery productivity (Gill and Wilhelmsson 2018). Human factors, such as fisher activity, other marine uses, and management applied to marine areas where OWFs are sited, can ultimately influence fisheries species (Gill et al. 2020). Changes, whether positive or adverse, may manifest during an OWF development phases and therefore temporal and spatial aspects were also considered as relevant. Several indirect evidence records (11%) provided an overview of expected OSW-related changes to the marine environment. Some of these sources considered the whole ecosystem, while others focused on specific topics, that is, noise, or dealt with other types of renewable energy or sector. Finally, co-existing activities were also included as they may have consequences for the fisheries species, whether the outcome for those activities is co-location or displacement.

The topics covered were consistent irrespective of geographic location. There were studies from 17 countries, mostly northern Europe, but regional studies on the southern North Sea and the Yellow Sea were also included. Except for some local factors, such as particular target species, the abiotic and biotic processes expected to change in association with OSW were generally similar, and the factors explaining these changes were also generic.

The OWF development phases covered by the indirect evidence were primarily construction (including pre-construction studies) and operation, few extrapolated to decommissioning scenarios. While we did not include decommissioning, we do recognise that it has the potential to cause significant ecological changes (Birchenough and Degraer, 2020) and will require attention in the future when more evidence is available.

4 | Discussion

4.1 | Direct Evidence

Considering that the first OWF was constructed in 1991 (Vindeby, Denmark), there is surprisingly little *direct* evidence on the impacts on fisheries species. We retained just 60 journal articles and reports since 2005, with 247 evidence records. The search did return more reports containing direct evidence, but these were earlier versions of updates from the same monitoring programmes so duplicated evidence provided in the later reports or papers linked to the reports (in these cases we always retained the most recent evidence source). What evidence there was showed no substantive effects (50% of records), difficult-to-interpret evidence (i.e., inconclusive, 30% of records) and inconsistency (i.e., multiple records giving different results for the same parameter). Impacts—whether regarded as positive or adverse—were identified in only 27% of records, and were frequently inconsistent within fishery level parameters (e.g., for quantity of demersal and reef-associated roundfish and demersal flatfish) and organism level parameters (e.g., one positive result for European plaice abundance) (Buyse et al. 2022) was accompanied by one neutral result (Buyse et al. 2023) and outweighed by four no effects records (Ashley 2014; Van Hal, Griffioen, and Van Keenen 2017; Wright et al. 2020; Degraer et al. 2021; see Table S2). This highlights the importance of considering the evidence base wider than just single studies, to fully understand the complex interactions between OSW and fisheries.

The evidence for finfish far outweighed that for invertebrate species (78%) which may reflect the diversity of finfish species fished globally combined with survey priorities and the types of fisheries operating in OWF locations. Elasmobranchs were very poorly represented at only five records, and only two of these were at the species level (thornback ray abundance (Wright et al. 2020) and winter skate catches (Gervelis et al. 2023)). More evidence is needed across the board, but particularly for elasmobranchs.

None of the fishery types achieved high confidence, meaning that none had more than five records providing consistent evidence on a specific parameter. Very little evidence focussed on stock-level parameters of landings and commercial catches; the majority reported on measures of quantity (i.e., abundance, density, survey catches or biomass). We argue that stock-level parameters urgently deserve specific attention in OSW-related routine monitoring of effects and targeted research projects since, in some regions, OSW has existed over the decadal timescales required for interrogating fisheries statistics.

4.2 | Indirect Evidence

Far more indirect evidence was found compared to direct evidence. This distinction between direct and indirect evidence ensured objectivity and further helped identify important knowledge gaps and recommendations to understand potential impacts of OWFs on fisheries species (see Section 4.3 and Table S3).

Indirect evidence studies fail to demonstrate an evidence-based link between the measured effect and a change at the population or stock level (see Table S3). Such changes will likely need to follow one or more cause-effect pathway(s) to explicitly link effect to impact (Gill et al. 2020). A good example is the study by Dannheim et al. (2020) determining OWF effects leading to meaningful impacts on the benthic ecosystem. By following a cause-effect approach, the cause and the effects are linked by pathways supported by evidence. This approach would allow indirect studies of fisheries and OWF interactions to provide context, highlight key findings and guide next steps to fill critical knowledge gaps. Studies of indirect effects would benefit from clearly setting out measurable parameters relating to fisheries species that link the study outputs to a population-level outcome that can be confidently associated with OWFs.

4.3 | Key Considerations

While some direct evidence of OSW affecting fisheries species was found, few records demonstrated impacts, whether regarded as positive or adverse, at a population or stock level. This is a critical shortcoming of the current knowledge base, which limits the determination of impacts.

To establish whether an effect can be deemed to be an impact to fisheries species, there must be evidence of measurable changes in production or stock parameters according to agreed, meaningful indicators of change—for example, demonstrable change in recruitment over at least 5 years of a time series. Furthermore, such changes must be confidently attributed to OSW. For instance, some demersal and reef-associated and demersal flatfish species appear to show increased presence within OWFs without detriment to the adjacent areas; however, clear evidence of consistent changes across different fisheries species is lacking. Furthermore, increases in abundance leading to greater biomass or spillover into adjacent areas, are often stated or predicted (Halouani et al. 2020) but this has not yet been evidenced

(Bonsu et al. 2024). Current policies, whereby resources to undertake site-based studies of fish species associated with each OWF development are assigned, could be adjusted, so that study efforts are coordinated, to take in wider perspectives and include areas that enable the determination of such production-related effects.

The current knowledge base is largely limited to adult fish life stages, however in order to truly improve our understanding of OWF effects on fisheries species, the early life history fish habitats, such as spawning or nursery areas, needs to be considered. Effects from disturbance of these habitats could propagate through the fish life cycle and have subsequent impacts at population-level. For example, changes to local hydrodynamics and sediment transport patterns could reduce the suitability of spawning areas.

The artificial-reef effect and fish aggregation concepts have been proposed for OWFs, and there is some evidence that developments do indeed attract some species of commercial or recreational fisheries interest (similar to oil and gas platforms—Claisse et al. 2014). However, to ascertain whether artificial-reef effects result in impacts to fisheries species, local aspects must be considered, such as range of OWF-related habitats, composition of fish communities, and their association with the OWF (Gill and Wilhelmsson 2018). The presence of hard vertical structures, namely turbine foundations, scour and rock armour protection, and subsea cables, act as attractants resulting in locally increased abundance of some species. Generally, diversity is expected to increase towards structures (e.g., Wilhelmsson, Malm, and Öhman 2006) and this appears to be the case for demersal fish associating with OWF vertical foundations and scour protection (Knorrn et al. 2024). However, recent evidence shows the importance of accounting for temporal variability, as species occurrence may vary on a diurnal basis (flatfish at Belgian OWF; Buyse et al. 2023) or according to season or life history (cod at German OWF; Gimpel et al. 2023). Therefore, data regarding the spatial occurrence of local fish assemblages linked with OWF structures must demonstrate artificial-reef impacts and account for temporal use of the structures by species.

Improving the direct evidence base does not necessarily mean a requirement to resource a whole new set of studies. Given that resources are scarce we suggest that existing studies set within the context of direct impact, as defined earlier, could be adjusted to ensure they address the required fisheries parameters. As highlighted above, some of the indirect studies could have been categorised as direct studies had they contained specific relevance to OSW rather than an unrepresentative association. A strategic and coordinated approach has been the most successful so far at providing direct evidence, through the research and monitoring programmes undertaken in Belgium and the Netherlands (e.g., Degraer et al. 2021). Such an approach is influencing scientific research and monitoring plans associated with the early phases of USA OSW development (see Lipsky et al. 2024) and a strategic approach has recently been set out by ICES in their Offshore Renewable Energy Roadmap. This roadmap acknowledges the need for a regional ecosystem-based management of OSW and fisheries (ICES 2024).

While we focussed on direct evidence of OWF effects on fisheries species, we acknowledge the importance of long-term indirect effects. In particular, the increased benthic biodiversity associated with OWF structures (Knorrn et al. 2024) and the potential "biofilter effect," concentrating secondary production at the scale of individual turbines (Mavraki et al. 2022). This change in local production could alter associated plankton and detritus-based secondary production, and therefore prey and predator dynamics involving fisheries species (Degraer et al. 2021). Such changes to the ecosystem highlight that to determine any impacts on fisheries species it is necessary to understand the influence of trophic effects (i.e., fisheries prey) and the extent of those effects, spatially or temporally. While a challenging task, it could be tackled strategically, using an overarching systems-based approach to guide a series of interconnected studies targeted at the key elements of these trophic effects (as suggested by Gill et al. 2020). A good example is the portfolio of interconnected research projects in the Belgian North Sea associated with OSW and national policy priorities (see Degraer et al. 2021). This ongoing programme of research is now in its second decade, delivering targeted research addressed at stakeholders and policy. While it is focused on the local ecological changes within Belgian waters, some of the research is relevant to fisheries species (and, interestingly, provided much of the evidence base extracted here). We suggest that other nations should have a similar policy to direct resources to research and survey programmes of fisheries species. In addition, a cross-border, regional-scale approach would be a must to appraise fishery effects at a population and stock level (see potential opportunities identified in the ICES ORE Roadmap; ICES 2024).

Other important knowledge gaps include the scaled-up effects of changes to transport and mobility across the different life stages of fisheries species and the connectivity introduced by hard structures. This includes spawning migration, larval transport from spawning to nursery to recruitment grounds, and OWF affinity and residence at different life stages (Gill et al. 2020).

A combination of methods may be required for studying the effects of OWFs on different life stages. Fish telemetry has been used for studying occupancy of adult stages of commercial species (Reubens et al. 2013), which is applicable to long-term monitoring of connectivity between OWFs and other fish habitats. Other methods are required to study larval/juvenile presence and colonisation dynamics, using reference areas to determine enhanced local production of benthic and foraging species and selected commercial species. Physiological traits and parameters of health and condition at all life stages could be used to determine population effects within and outside OWFs; this data could be used to validate population models of seasonal movement, growth, reproduction, recruitment, and natural mortality for fishery species (Provot et al. 2020).

In the case of shellfish, there is evidence of high abundance taking advantage of OWF structures (e.g., crustacea: Roach et al. 2018, Krone et al. 2013; bivalves: Kerckhof et al. 2019). However, studies fail to demonstrate that abundance increases are long-lasting because they do not measure the changes for sufficient time. Therefore, the evidence is restricted to the duration of the study period, or, alternatively, they fail to demonstrate how higher local abundance (or biomass) shellfish translates to production at larger, regional scales. Furthermore, increased local abundance may occur owing to translocation from elsewhere, hence resulting in net zero increase for the fishery.

Finally, data on fishing fleet activity and management quotas per fleet are key to fully ascertain any OSW impacts to fisheries species and to anticipate potential changes in target species, by modelling seasonal and spatial changes of fishing effort in response to availability of fisheries species and fishing mortality.

4.4 | Recommendations for Determining Impact

We recommend that to determine OSW impacts on fisheries species it is fundamental to establish whether observed changes are directly evidenced or inferred from indirect evidence. There needs to be a concerted effort towards targeted monitoring and survey strategies to understand whether impacts occur to fisheries species (as proposed by Cresci et al. 2024; Lipsky et al. 2024); that is moving from inferring to evidencing. Indirect and inferred studies do, however, help flag knowledge gaps and guide how to determine potential impacts. Methods need to be relevant to commercial stocks and populations, and capture before and after OWF construction data (Lipsky et al. 2024).

Current OWF monitoring studies of fisheries species typically look at one to 2 years pre-construction compared to between two to 5 years (inconsistently; see MMO 2014), but these timescales are more suitable for detecting abrupt regime shifts (Spencer et al. 2011), rather than the more gradual, long-term changes and trends on local species and communities (Weijerman, Lindeboom, and Zuur 2005; Spencer et al. 2011). The use of appropriate spatio-temporal monitoring approaches and analytical techniques is therefore a recommended prerequisite, which should be embedded into policy to ensure consistent data collection within monitoring studies to achieve a higher confidence in the outcomes (as proposed by Lonsdale et al. 2022).

As our SE has highlighted, there is a distinct lack of evidence of OSW impacts on fisheries species, which emphasises the urgency for furthering the evidence base. Data collection should be targeted towards identified gaps, and survey methods standardised and strategic, integrating OSW- and fisheries-relevant areas under the principles of cumulative impacts assessment (Gill et al. 2020; Willsteed et al. 2018). Fisheries are generally managed using regional-scale approaches, and data from OWF monitoring should be similarly scalable for compatibility. Evidence suggests that OWF effects vary with distance from the OWF, and a Before-After-Gradient (BAG) approach is recommended rather than the standard Before-After-Control-Impact (BACI) design (Methratta 2020). In addition, due consideration should be given to standardisation, storage and accessibility of data and information (Lipsky et al. 2024).

During the time of undertaking this review, evidence of OSW effects on fisheries species was extracted from a few studies from a rather restricted cluster of research groups and locations. Some OWFs have been very intensively studied, such as some Belgian and Dutch ones, providing a well-founded knowledge base for these localities although most are limited to single-turbine effects, or to single OWFs, then extrapolated to infer fishery effects at a larger scale. While this scaling-up may be acceptable for territorial, sedentary and sessile species (acknowledging dependence on life history and local conditions), it is less applicable to mobile and wide-ranging species. Predictive models show that the effect on species with greater reliance on OWFs-associated habitat can be disproportionate compared to more mobile species (Friedland et al. 2021). Confidently determining OSW impacts as changes to fishery populations or stocks will likely require regional approaches.

5 | Final Remarks

While writing this manuscript, a few relevant new studies were published on direct effects that were included in the discussion. It is important to note; however, that all these studies concur with our systematic evaluation and conclude that there is limited evidence of OSW's effect on fisheries species, echoing our call for improved data collection for fisheries species associated with OSW developments. This will essentially demand novel methods, rather than traditional scientific surveys, (Lipsky et al. 2024; Gimpel et al. 2023) if we are to determine impacts on fisheries species, particularly given the impending widespread expansion of OSW in the global marine environment.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors confirm that this article does not utilise shared data or data held elsewhere.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.