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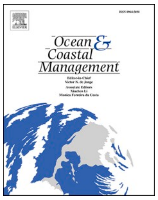

Review

The global impact of offshore wind farms on ecosystem services

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ABSTRACT

Understanding the global impact of offshore wind farms (OWF) on biodiversity and ecosystem services (ES) is crucial in developing sustainable energy transition pathways. This study takes a holistic approach, coupling a semi-systematic review with a novel analytical methodology, to consider the consequences of construction & operation of OWF deployment on biodiversity and ES. 314 pieces of evidence taken from 132 peer-reviewed studies provide the basis to determine the ecological and ES impacts. The process showed that construction impacts were predominantly negative across the ecological subject groups (52%), compared with positive impacts (8%) with several species of fish (e.g. brill, cod, dab, plaice) and some species of birds (e.g. common guillemot, northern fulmar, redhead) showing strongly negative trends. Operational phase impacts were more variable and could be either negative (32%) or positive (34%) depending on site specific conditions. More detailed investigations into fish, shellfish, humans and air-surface studies recorded a net positive effect of wind farm operations on these subject groups. Translation into ES outcomes identified that 14 ES are impacted by the construction and operation of OWF. The most substantially enhanced ES included effects on commercial fisheries and experiential recreation. Social acceptance toward new and hypothetical OWF was also strongly positive, irrespective of country location. Negative effects on ES, including existence values for culturally important groups, e.g., marine mammals and birds and the spread of non-native species, are potentially of most significance. Overall, this study finds more than 86% of possible offshore wind farm impacts on ES are still unknown. There was also a paucity of studies on the decommissioning of OWF and the impacts of deeper-water floating structures, with a bias in studies toward northern hemisphere and developed countries.

1. Introduction

Anthropogenically-induced climate change is fast becoming one of the biggest drivers of biodiversity loss, and the substantial expansion of offshore wind farms (OWF) is central to tackling both these interconnected crises. Many countries around the world are busy planning considerable expansions in the scale and extent of OWF which, if done sustainably, could accelerate the energy transition, help meet international net zero emission targets by 2050, while also potentially having positive effects on local biodiversity by facilitating nature recovery actions (ter Hofstede et al., 2022; Virtanen et al., 2022). To meet net zero emission targets by 2050, it is estimated that 2000 GW of OWF will need to be installed worldwide, up from a mere 35 GW of installed OWF in 2020 (GWEC, 2022). This would require around 5000 new turbines installed each year occupying more than 500,000 km^2 of ocean by 2050 (Putuhena et al., 2023). Historically, only a few countries – including the UK, Germany, the Netherlands, Denmark, Belgium, China and, USA – have made notable progress to advance and deploy OWF, but this is set

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Abbreviations: ES, Ecosystem services; OWF, Offshore wind farms; MPAs, marine-protected areas; BNG, Biodiversity Net Gain; EIA, Environmental Impact Assessment; EMF, Electromagnetic fields; QAF, quality assessment framework.

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to change in the coming decade with countries including Australia, Brazil, France, India, Italy, Poland and Saudi Arabia all aiming to build their first OWF by 2030 (GWEC, 2022).

It has been suggested that, if appropriately managed and designed, the future deployment of OWF may increase biodiversity and may have the potential to produce positive environmental benefits for society (e.g. Inger et al., 2009). Some studies have found that the foundations of OWF structures act as artificial reefs and fish aggregation devices (Langhamer, 2012; Degraer et al., 2020), providing space for the settlement, shelter and foraging for some animals (including pelagic and demersal fish, marine mammals, juvenile corals and other benthic sessile invertebrates). Likewise, by restricting activities that can negatively affect the environment, offshore wind farms can act as an *de facto* marine-protected areas (MPA), which can potentially enhance both biodiversity and commercial fisheries in surrounding areas (Ashley et al., 2014; Buyse et al., 2022). Yet, while on a global scale the advantages of decarbonization *via* OWF energy are not in doubt (Sherman et al., 2020; Victoria et al., 2020), it is recognized that such a rapid transition risks a wide range of unintended negative environmental consequences, both locally and across the world. Concerns over the potential impacts of OWF installations on the local environment have been increasingly reported in a number of studies and include: habitat loss, collision risks, noise and electromagnetic field impacts, introduction of invasive species and visual or aesthetic impacts which may affect both human and animal populations in the vicinity of OWF turbines (e.g. Bailey et al., 2014; Lloret et al., 2022; Teilmann and Carstensen, 2012). As the size and scale of OWF increases, the risk of significant cumulative effects arising is also expected to increase (Brignon et al., 2022; Gușatu et al., 2021).

Despite research on OWF growing exponentially over the last 20 years, the net positive or negative impacts of OWF on many marine populations remains unclear (Willsteed et al., 2018). Moreover, there is a need to better understand the wider socio-economic, health and cultural impacts of this expanding sector to support the development of wider energy and environmental policies. The ecosystem services (ES) approach is a broad method designed to capture and define the benefits people derive from nature (Haines-Young and Potschin, 2018). In the case of OWF, the ES approach sets any ecological impacts within a societal and economic context, assessing which ecological impacts may affect human well-being. This ensures that the full ramifications of ecological change are included when development options are considered, and enables holistic, evidence-based trade-offs can be made in decision making. ES are typically divided under various classifications such as the Common International Classification for Ecosystem Services (CICES; Haines-Young and Potschin, 2018) into provisioning services (e.g. food, fibre, minerals), regulating services (e.g. waste-water treatment, carbon sequestration and storage) and cultural services (e.g. recreational and aesthetic interactions). Habitat and supporting services (e.g. life-cycle maintenance, habitat provision) are also commonplace in several ES classifications and are considered to underpin all other services (Beaumont et al., 2007). Several recent studies (Hooper et al., 2017a; Papathanasopoulou et al., 2016; Trifonova et al., 2022) highlight the poor understanding of the holistic effects of OWF energy systems and technologies on ES delivery and that such impacts are rarely considered through a whole-ecosystem perspective. OWF structures are often highly spatially aggregated, limiting understanding of larger-scale implications for ES provision which is often highly context dependent (Holland et al., 2018). The impact of OWF is, however, a global issue, and a synthesis of the information currently available across multiple spatial scales and locations is therefore required to better understand global cumulative ecological impacts and also the wider societal and economic consequences.

The systematic review process aims to produce an unbiased synthesis using available academic research on a particular topic (Petticrew and Roberts, 2005), often with the aim to guide decision making. This approach, along with associated statistical methods (e.g. meta-analysis) to summarize the results, have been increasingly promoted as central to assessing the impacts of marine renewable energy structures (Methratta and Dardick, 2019; Peters et al., 2020). In this study we undertook a semi-systematic review of published global research on the environmental and socio-economic effects considered in assessment of the impacts of offshore wind farms OWF. The proposed review aimed to answer the following two primary questions: 1. What peer-reviewed published evidence exists for the effects of marine OWF structures on biodiversity and ecosystem services? 2. What published evidence exists for the effects of the construction, operation and decommissioning of marine OWF structures on the marine ecosystem? The review then analyzes and discusses some of the opportunities, data confidence issues and trade-offs in terms of biodiversity and ES that might need to be resolved if the OWF sector is to move forward in a sustainable manner. This understanding is integral to ensuring that international decisions on the next generation of OWF will be based on the most comprehensive information and will aid policy obligations that require all 'new' infrastructure development projects to ensure either a net gain of biodiversity (BNG), the environment or ES all targets which are becoming common globally (e.g., Aichi Biodiversity Targets (Convention on Biological Diversity, 2011–2020)). The aim of such targets and approaches is to leave biodiversity and ES in a similar or better state than before infrastructure development, while also securing wider benefits for people and the environment. As such, this research is intended as a stage of advancement towards building a more complete and detailed understanding of the balance between positive and negative changes for both biodiversity and ES caused by different stages of OWF development.

2. Materials and methods

2.1. Updating and exploring the global evidence-base around OWF

This study builds upon two previous existing systematic reviews (Hooper et al., 2017a; Papathanasopoulou et al., 2015) and a more recent systematic map developed by the authors of this study (Lemasson et al., 2021, 2022) to update the growing evidence base on the impacts of OWF globally. A formal systematic review process was followed (Lemasson et al., 2021) as was a standardized protocol (Bayliss et al., 2016) for updating and amending existing systematic reviews and systematic maps in environmental management (detailed in Appendix S1). This included consideration of a wide array of observational, modelling and empirical data which provided 314 pieces of evidence taken from 132 studies. Structured search terms and search engines used to gather the data are described in (Appendix Table S1). Reports from grey literature sources were excluded here due to: i) the difficulty in accessing grey literature from multiple countries around the world, and ii) most of the grey literature evidence base related to OWF is often based on environmental impact assessments (EIA) which can lack peer-review, quantitative assessment or are not freely available (Lemasson et al., 2023; Vaissière et al., 2014). A separate comparison study between the UK's published OWF impact evidence (using data from this study) and available grey literature is discussed separately by Szostek et al. (2024). The focus here is thus on evidence derived from published peer-reviewed articles with respect to the effects of constructing, maintaining and decommissioning OWF globally (detailed in Appendix Table S2).

The geographic locations of the studies included, alongside future OWF installation goals by country to 2030, are shown in Fig. 1 and grouped to each countries' Exclusive Economic Zone (GWEC, 2022). It is notable that the majority of the research studies undertaken on OWF are grouped in the Northern Hemisphere, particularly from the UK (58 studies), Germany (49 studies), Denmark (47 studies), Belgium (46 studies), the Netherlands (46 studies) and the USA (45 studies). However, the proportion of future offshore wind farm installations by 2030 are clustered around not just the UK (50+ GW), EU (80+ GW) and the USA (38+ GW) but also in areas such as Australia (2+ GW), Japan (10+

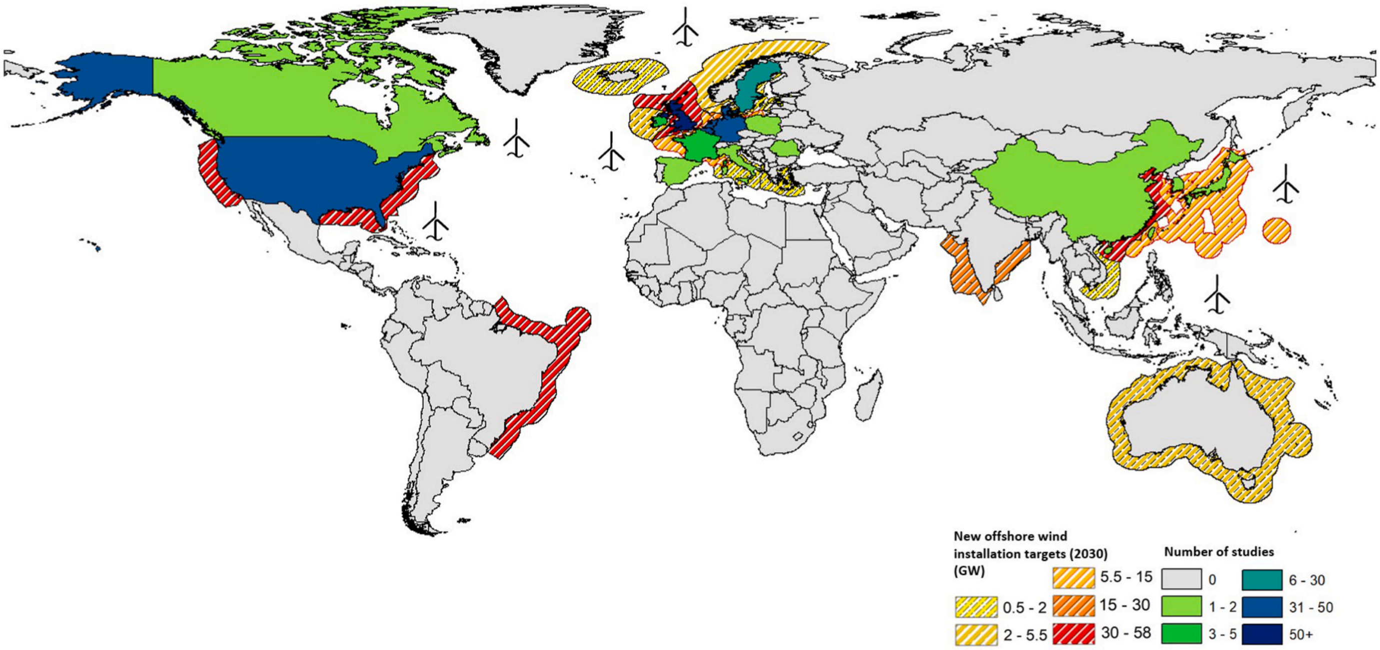

Fig. 1. Global research into the effects of OWF on ecology and society, including future installation trends by country to 2030 (GWEC, 2022).

GW), South Korea (12+ GW), Brazil (42+ GW) and China (58+ GW). Table 1 provides an overview of how the 314 pieces of evidence were allocated between the 9 subject types, and 18 different outcomes. These were further subdivided based on outcomes during construction and operation. For example, there were (n = 25) data points relating to fish focused on the direct effects of construction of OWF structures, (n = 16) on abundance and (n = 9) on noise related effects. The majority of studies related to fish, birds and marine mammals and on how the physical presence of turbines affects species abundance and distribution (e.g. barrier effects). For publications that considered more than one

Table 1
Heatmap of semi-systematic review. The 314 pieces of evidence were organised into 9 subject types (based on primary topic of research) and 18 different outcomes (based on primary effects of OWF). These were further subdivided based on outcomes during construction (C) and operation (O). Darker green cells indicate most studies; while red cells indicate fewest studies.

Subject Types	Outcomes																		
	Barrier effect		Behavioural disturbance		Changes in water quality		Changes to the hydrodynamic regime		Collison risk		Displacement habitat loss		Electromagnetic fields (structure or cables)		Fish and shellfish exploitation		Human health and wellbeing		
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	Total
Air–sea interface	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Birds	10	34	1	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	48
Benthic sediment	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	3
Fish	0	1	0	1	0	0	0	0	0	0	0	1	0	4	0	5	0	0	12
Humans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	3
Macro invertebrates	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	7
Mammals (Bats)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mammals (Marine)	3	2	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	7
Shellfish	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0	0	0	0	4
Total	13	37	1	1	0	1	0	3	1	2	0	4	0	13	0	6	0	2	**84**

Subject Types	Impacts on seascape (aesthetic/visual)		Impacts on seascape (sense of place)		Introduction of non-native species		Noise disturbance		Other		Presence of structure/ abundance of biota		Presence of structure/community structure		Sedimentation		Social acceptance		Total
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	Total
Air–sea interface	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	5
Birds	0	0	0	0	0	0	0	0	0	0	1	13	0	0	0	0	0	0	14
Benthic sediment	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	4	0	0	7
Fish	0	0	0	0	0	0	9	0	0	0	16	55	0	2	0	0	0	0	82
Humans	0	12	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	24	40
Macro invertebrates	0	0	0	0	0	11	0	2	0	1	3	24	0	4	0	0	0	0	45
Mammals (Bats)	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	4
Mammals (Marine)	0	0	0	0	0	0	12	5	0	0	3	4	0	0	0	0	0	0	24
Shellfish	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	9
Total	0	12	0	2	0	11	21	7	0	4	23	114	0	8	0	4	0	24	**230**

outcome or subject group, each piece of evidence was considered separately. By comparing subject type with the OWF lifecycle stage, it was evident that most studies have been focused on the operation phase (81%), followed by the construction phase (19%), while no peer reviewed studies were found that empirically assessed the decommissioning of OWF.

2.2. *Global ecological impact assessment*

The metrics used to record environmental, ecological and social outcomes or effects of OWF in the reviewed studies were too inconsistent and variable to undertake a formal statistical meta-analysis of the data. Instead, the findings were grouped by direction of impact, according to whether the observed impact on the subject was statistically negative, positive, no-impact or inconclusive following the methodology of Papathanasopoulou et al. (2015) & Hooper et al., (2017). The latter category reflects where there is no clear trend in the effects reported within the study, for example, trophic changes in food webs can have complex cascade effects that are not often transparent based on singular response data (Watson et al., 2020). The potential direction of impacts on habitats, biota and humans were grouped to the lowest possible subject level (often species or group level) according to the lifecycle stage of the stage of the technology (i.e., construction and operation). As all the papers are peer-reviewed, this provided a basic level of quality assurance, but owing to the extensive variability in the methods applied, it was considered necessary to further assess confidence in the gathered studies. To objectively assess the quality of the studies, and as a basis on which to judge the reliability of the impact results reviewed, a quality assessment (QAF) framework was adapted from Pullin and Stewart's guidelines for systematic review in conservation and environmental management (Pullin and Stewart, 2006). Studies were assessed using significance scales based on four quality assurance attributes: 1) scale of study; 2) study design (comparator); and 3) type of study, each scored from 1 lowest confidence to 4 highest confidence. A total ecological confidence score was then determined by summing these individual scores and combining with available evidence points (see Appendix 1 S2 for the method and Tables S3 and 4 for the results).

2.3. *Translation to ecosystem services impact*

The impact on each ecological subject group was then translated into ES terms using the CICES framework (Haines-Young and Potschin, 2018) version 5.1. CICES (see Appendix 1 Table S5), with the main categories of ES being: provisioning, regulating and cultural. Here, these were expanded into seventeen smaller group divisions, based on ES with relevance to marine environment. The CICES framework only considers final ES that have direct value to people. However, many of the impacts of OWF developments affect the underlying ecological functions or supporting services that ultimately give rise to ES, e.g. the biophysical structure of biota around turbines. In order to accommodate these intermediate services, the CICES classification was supplemented by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2003) category of supporting services. These supporting services were divided into two generalised groups: 'biodiversity' effects and 'habitat quality' effects depending on the structures' influence on biota or the general sediment environment. For ease of communication, have sub-divided and re-named the ES of carbon sequestration and storage from of wider CICES ES of climate regulation as a there was a predominance of studies just looking at carbon as opposed to more weather and water movement related elements of this service.

Public acceptance and the importance of local identities have increasingly become recognized as a key consideration within natural hazard risk reduction policy (Anderson and Renaud, 2021). Such categories are also not fully 'counted' as final ecosystem benefits in the CICES 5.1 framework. Therefore, to capture these wider cultural aspects, two further groupings 'sense of place' and 'social acceptance' were included based on the suggestions and guidance of (Ryfield et al., 2019; Hooper et al., 2020) respectively. The impact of OWF on each ecological subject group was then combined with the ES classifications following the methodology of (Papathanasopoulou et al., 2015). A full example of the translation to ES outcomes for all ecological subject groups is provided in Appendix 2. Similarly, to the ecological synthesis, the ES assessment produced a qualitative output based on potential changes to ES, where the direction of the potential change in ES provision is recorded as degraded, enhanced, no change or unknown (see Appendix 1 S3 for the method). In addition, if more than 50% of studies suggested a strong or substantial effect on that service, it was then categorized in more detailed analysis below as "substantially enhanced" or "substantially degraded".

3. Results and discussion

3.1. *Ecological impact synthesis*

3.1.1. *Construction impacts*

The majority of the construction impacts were negative (52%, Fig. 2) across the subject groups (with several species of fish (e.g. brill, cod, dab, plaice) and some species of birds (e.g. common guillemot, redhead) showing strongly negative trends. Exceptions to these trends included no impacts on some fish species (e.g. pouting) and some bird species (little gull), and positive effects on certain species of gulls (e.g. herring gull, lesser black-backed gull). Overall, 8% of construction impacts had a positive outcome on biodiversity. Inconclusive impacts (24% of studies) were found during the construction of OWF for the Atlantic herring (*Clupea harengus*) and Pacific herring (*Clupea pallasii*) which are commercially and culturally important globally (Fig. 2). A summary of the OWF ecological confidence data scores is given in Tables S3 and S4 and demonstrates that there is limited global peer-reviewed evidence of OWF construction effects on shellfish, benthic sediments, bats, humans, and effects occurring at the air-sea interface (Table S3). Evidence was also lacking during the construction phase for macro-invertebrates (poor: 5.7), fish (moderate: 8.2) and birds (moderate: 9.9), while the best studied subject was the marine mammals' (cetacean) group (good: 10.5).

3.1.2. *Operational impacts*

Overall, across all subject groups the positive and negative operational effects were evenly balanced with 34% of effects ranked as positive outcomes, while 32% were assessed as negative (Fig. 3). Approximately a quarter of all effects were classified as having no impact on subject groups across operational (26%) studies. More detailed investigations into fish, shellfish, bats, humans and air-surface studies reported a net positive effect of OWF operations on these subject groups. Positive impacts, on enhanced abundance of populations, were recorded for two commercially important species, cod and pouting. The general public of various countries and recreational fishermen also cited enjoyment of the OWF as an enhanced fishing location, due to increased catch and cultural-related aspects of the structure (Fig. 3).

In contrast, the majority of impacts on birds, macro-invertebrates and sediments were negative, with a number of studies detecting reductions in abundance, biomass and diversity of bird and benthic species around OWF. The transport and mobilization of sediment plumes during the construction of OWF is another observation recorded in a limited number of studies (e.g. Christie et al., 2012). Negative associations were also reported by local residents who live next to OWF structures (as opposed to the general public who can live inland from structures) and by commercial fishermen. Only marine mammals recorded overall no effects from the operation of OWF, although for some species, such as the Harbour porpoise, these effects were variable across studies (Fig. 3). The operational studies considered a wider range of subject groups (Table S4) with a mix of poor, moderate and good confidence scores recorded on outcomes such as: the air-sea interface, birds, humans,

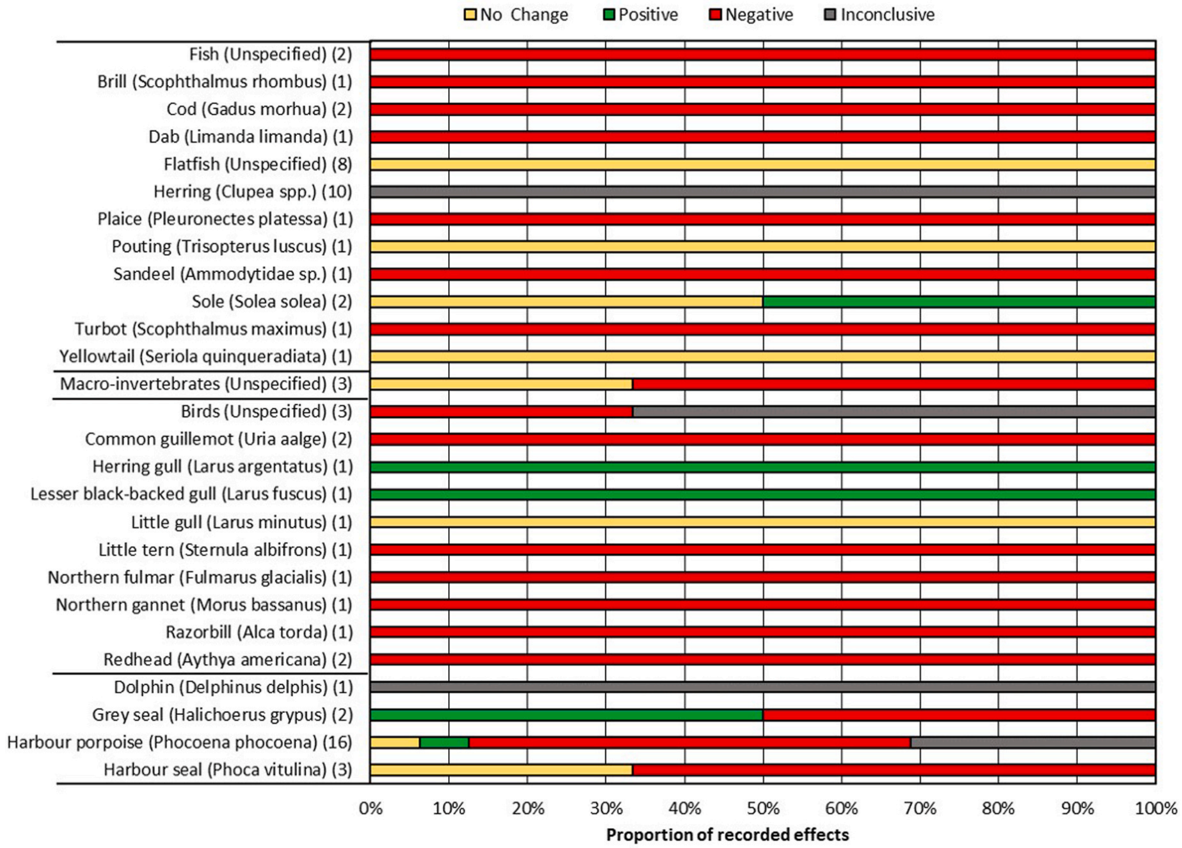

Fig. 2. The potential direction of impacts on biota from offshore wind farm construction. The number of data points (not studies) is given it the brackets.

macro-invertebrates, shellfish (moderate: 7.2–9.6); bats (poor: 4.0); fish and benthic sediments (good: 10.4–11.4).

3.2. Ecosystem service impacts and social acceptance

A summary of the results shows fourteen ES are impacted either positively or negatively by the construction and operation of OWF (Fig. 4) across the nine investigated ecological subject groups. Species-specific linkages to ES are aggregated in Fig. 4 to their highest available subject level e.g. Harbour porpoise (*Phocoena phocoena*) would be grouped to marine mammals (more detailed species-specific linkages to ES can be investigated in Appendix 2). A potential negative impact on all ES is identified during the construction phase, except for the biodiversity of non-commercial fish populations. From the results in Fig. 4 (selecting services enhanced (dark green) or degraded (dark red) impact scores), we identified four ES with specific opportunities or values at risk from deploying OWF. Although not specifically an ES, the responses from opinion surveys on the social acceptance of OWF development are also substantially positive and are therefore discussed in detail alongside the four highly impacted ES:

3.2.1. Provision of wild food and fisheries

The ES of wild food is here defined using the CICES framework as "wild food collected for human consumption". Where studies indicated an effect on a commercially important species, but did not link the change directly to human wellbeing (e.g., by using fish catch or landings data), these effects were considered to be impacts on the supporting service of biodiversity. Changes to wild fish stocks and commercial fisheries, that ensue from OWF developments, can be positive or negative depending on three types of direct effects on fish and fisheries: fisheries exclusion and displacement effects, physical energy effects (i.e. electromagnetic fields (EMF), wave and currents), and artificial reef effects (Gill et al., 2020). Studies on impacts during the construction phase were strongly focused on commercially important species of fish, with evidence of strong declines in cod, plaice, dab and sandeel landings due to displacement effects after OWF construction (Fig. 4). The observed overall negative effects do not extend to all species, with no evidence that sole and pouting landings were affected during the construction phase.

Conversely, observed landings of cod, pouting and other commercial sessile and mobile benthic macrofauna (e.g. blue mussels and brown crabs) increased during the operation phase of OWF. This suggests it is possible for commercial fish species to benefit from OWF structures (see Langhamer, 2012; Degraer et al., 2020), potentially resulting in increased food provisioning benefits for society. However, no OWF-related evidence was found in the studies reviewed on the linkages and mechanisms between increased fish production and increased fish landings, suggesting further research on such linkages is needed (e.g. Mavraki et al., 2021).

Negative EMF and acoustic effects of OWF were also recorded on several sensitive species during construction or operational phases (e.g. founder, sole, American lobster and various species of crabs) with most studies considering behavioural responses to pile-driving noise or EMF (e.g. Hutchison et al., 2020; Wilber et al., 2018) generated by operational OWF cables. None of these studies explicitly considered how these effects translate into wider societal benefits such as changes in commercial fish or invertebrate landings. Other absences from the global literature included references to altered condition and nutritional content of fish due to OWF impacts (Herbert-Read et al., 2022), with wild food contributing to cultural heritage, food security and dietary quality in many countries (Gee and Burkhard, 2010).

3.2.2. Pest and disease control, invasive species

There is mounting evidence globally that artificial structures, both

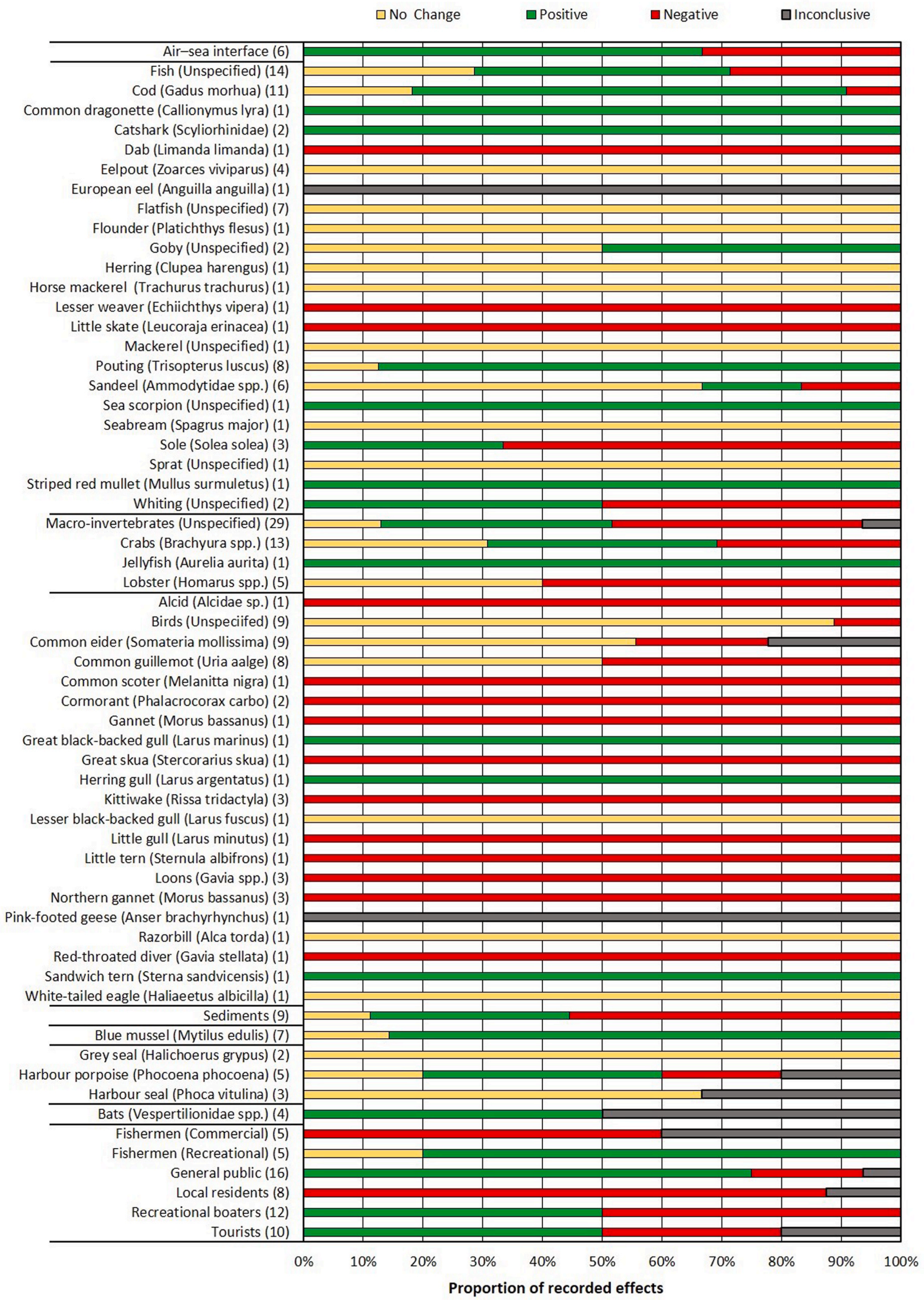

Fig. 3. The potential direction of impacts on biota and humans from offshore wind farm operation. The number of data points (not studies) is given it the brackets.

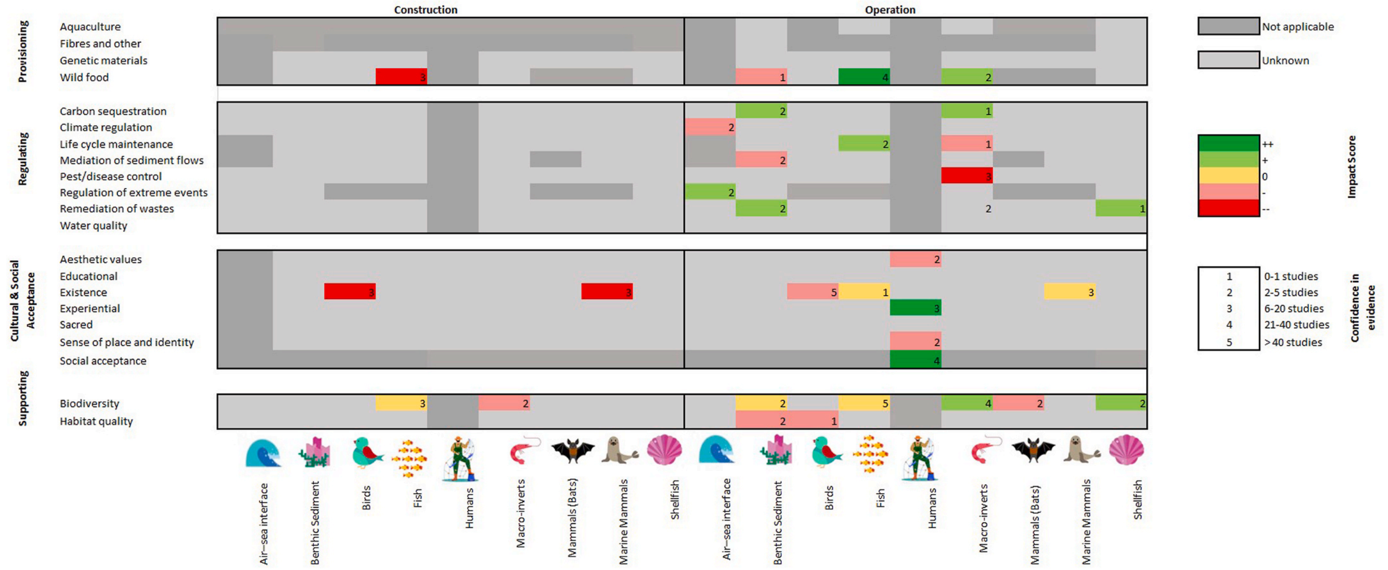

Fig. 4. Ecosystem service impacts of offshore wind farms during the construction and operational phase. The '- -', '-', '0', '+' and '++' scores denote a substantially degraded (dark red), degraded (light red), no change (yellow), enhanced (light green) and substantially enhanced (dark green) effect on the service, respectively. Light grey shading indicates that the relationship between the ecosystem service and subject is unknown (e.g., operation > macro-inverts > remediation of wastes). Confidence in evidence (1–5) relates to the number of available studies relating to each impact score.

coastal and offshore, function as prime sites for colonization by invasive or exotic species (Clubley et al., 2023; O'Shaughnessy et al., 2023) OWF, in particular, may have a negative effect on the ES of pest and disease control by introducing hard substrate (e.g. *via* foundations, mooring anchors or cables) which can provide stepping-stones for invasive species to expand further (Bulleri et al., 2006).This in turn can disrupt local food-web dynamics and spread additional diseases (De Mesel et al., 2015; Degraer et al., 2020), which can then potential impact local species. Several taxonomic groups of non-native species, including mussels, oysters, algae, jellyfish, sea urchins and various macro-invertebrates (e.g. sea squirts, amphipods, crustaceans and tube-building worms) were recorded on fixed OWF in the reviewed studies (Degraer et al., 2020). However, no OWF studies included in this review (up to January 2022) examined the potentially negative effects of invasive species that may attach on deep-water floating OWF (Farr et al., 2021), making these a research area of priority. However, since this review, a recent paper (Karlsson et al., 2021) has shown an absence of non-native species on floating OWF structures and overall similarities in benthic communities colonizing floating OWF with those on other artificial structures. Economic and social costs, including both commercially valued losses resulting from the spread of invasive or non-native species from newly developed OWF, were likewise nascent from this review. This is also much-needed area of investigation as co-location effects are likely to be an important factor in the future, given that OWF structures are increasingly being proposed as multi-use setting with commercial activities such as seaweed or bivalve cultivation.(van den Burg et al., 2020).

3.2.3. Existence values

The substantially degraded change in existence values (Fig. 4) — which can be defined as the enjoyment and philosophical perspective provided by the knowledge of, and reflections on, the existence of wild species, wilderness, or land-/seascapes (MA 2005)— in this study primarily relates to possible harm (e.g. via collision or entanglement by cables) to charismatic megafauna such as marine mammals (e.g. seals and dolphins) and seabirds, which can hold a cultural importance to individuals (Kontogianni et al., 2012; Loomis and White, 1996). The focus of research effort has predominately been on barrier and displacement effects (i.e. collision and avoidance) on seabirds and marine mammals within operational OWF. Articles describing avoidance of OWF areas by seals and Harbour porpoise as well as several bird species (e.g. Brandt et al., 2018; Newton and Little, 2009) during OWF construction are also prevalent in the peer-reviewed literature. However, the lack of clear patterns regarding the effects across and within bird and marine mammal groups (Figs. 2 and 3) suggests that displacement and disturbance effects are probably a species-specific issue, dependent on individual OWF characteristics (Forney et al., 2017; Marques et al., 2021). Such impacts will also be accompanied by a loss of human well-being (Fig. 4), with many individuals intrinsically valuing megafauna simply for knowing that they (or particular species) exist and are conserved, even if they never directly experience them (Börger et al., 2014; Klain et al., 2020). Yet, the studies reviewed cannot be unequivocally attributed to changes in existence values as, for example, they did not consider people's willingness-to-pay for the existence of an environmental resource or the potential wider economic impacts on tourism (e.g. seal or bird watching trips) that might occur due to displaced animals. Notably, OWF socio-ecological impact studies on several other charismatic megafauna groups such as elasmobranchs (e.g., sharks, skates, rays and sawfishes), marine reptiles (e.g. sea turtles) and certain groups of marine mammals (e.g. whales, dugongs, sea lions) were also virtually absent from the published literature. This is particularly concerning as ship strikes and cable entanglement already top the list of hazards for many endangered megafauna groups (e.g. right whale populations, Quintana-Rizzo et al., 2021) and more construction work, increasing vessel traffic, and future cables attached to floating wind structures, will likely combine to have cumulative impacts on these groups.

3.2.4. Experiential recreation

The expansion of OWF has given rise to increased concerns about space competition between different marine sectors (Hooper et al., 2017b). While regulatory authorities and OWF developers often focus on impacts of OWF on commercial fishing (as discussed above in section 3.2.1), members of the general public and businesses related to coastal tourism also raise concerns about OWF blocking boating routes or restricting available space for other recreational activities, such as recreational fishing or diving (Westerberg et al., 2013). Overall, this review suggests the alternative: that OWF in various countries (such as the UK, USA and Denmark) are functioning as an attractant, either as a novel sight or as a recreational fishing destination (Parsons et al., 2020; Smythe et al., 2021). Recreational anglers and beach users also had a positive attitude to existing OWF (Lilley et al., 2010) and value the OWF as symbolic of progress towards green energy (Smythe et al., 2021). However, the visual effect of OWF on seascapes was also raised as a key issue. There is initial evidence from the review that OWF are perceived to reduce the visual amenity of seascapes and this may negatively impact on people's 'sense of place' or connection to the ocean, with (Devine-Wright and Howes, 2010) finding that people give special significance to the ocean and desire to avoid intruding upon it. A strong caveat of the experiential recreation findings is that most of the research on this ES has been conducted in developed and northern hemisphere countries (e.g. UK, Germany, USA), thus more research is needed from other geographic context – particularly for southern hemisphere countries (e.g., Brazil, India and Australia) which have high future OWF deployment trends, while also being popular tourist destinations.

3.2.5. *Social acceptance*

Social acceptance is an essential yet often neglected consideration in the plans for new OWF developments (Inger et al., 2009; Rehbein et al., 2020), particularly at a local or regional level. The review identified that the general attitude towards new and hypothetical OWF among general public respondents appear to be strongly positive, irrespective of country location and experience of OWF. Existing literature on public support of OWF identifies the main drivers of positive acceptance factors are complex but include considerations of several ES (e.g. aesthetic or visual impacts, positive opportunities to improve biodiversity and the creation of new recreational activities) as well as several other socio-economic factors such as job creation, economic growth and wider community benefits (Kim et al., 2020; Ladenburg, 2008). In contrast, the main causes of rejection of OWF relate to the potential barrier and displacement effects of OWF structures (e.g. ten Brink and Dalton, 2018) particularly to commercial fishermen, with concerns over profitability and efficiency, technical feasibility and operational risks of fishing within OWF, and clarity on the access to natural capital resources (e.g. fishery rights to access fish stocks in OWF). These findings are largely based on studies of hypothetical OWF, suggesting clearer protocols of communication and compensation between sectors are likely needed to address co-location opportunities around new OWF developments, as suggested recently by (Hooper et al., 2015; Schupp et al., 2021).

3.2.6. *Other at-risk ecosystem services*

Beyond the most substantially enhanced or degraded ES recorded above, the development of OWF also has the potential to alter many regulating and supporting services (e.g. biodiversity and habitat quality) and the biogeochemical cycling of marine systems (De Borger et al., 2021). While macro-invertebrates and shellfish are likely to benefit from the presence of OWF (Fig. 4), birds are generally expected to be impacted more from habitat degradation and loss resulting from OWF operation than other species groups. Regulating services also have potential to be considerably affected during the construction phase, but Fig. 4 clearly demonstrates a large number of unknowns relating to the direction of impact on these services. Given global net zero ambitions, it is surprising that there have only been a handful of studies on the regulating service of carbon sequestration and storage and any impacts OWF many have on 'blue carbon' habitats (see Lovelock and Duarte, 2019). The available results do show that once built, the presence of OWF may lead to strong positive changes in the flux of nutrients, organic matter, and carbon both inside and outside wind farms. One study by (Ivanov et al., 2021) suggest that total organic carbon flux to the sediment can be increased up to 50% in an area 5 km around turbines, with a notable effect up to 30 km away. The long-term storage of carbon in the sediments around OWF is, however, still very uncertain and it is likely that the storage may be of limited duration if the seafloor is disturbed (i.e. the carbon is re-released into the water column), for instance, due to the impacts of trawling or if it is released following the decommissioning of the wind turbines (Smyth et al., 2015). One possible scenario to retain some of the sequestered carbon is partial decommissioning, where part of the OWF structure remains in place (Lemasson et al., 2023) but such assumptions still need to be tested empirically. Similarly, other regulating services may be affected, with a small number of studies suggesting OWF can impact sediment transport and downstream sedimentation (Vanhellemont and Ruddick, 2014), reduce extreme storm surges (Pan et al., 2018) and may even act as areas of low microplastics pollution (e.g. Wang et al., 2018). However, evidence regarding how OWF affects various subject groups (e.g., macro-invertebrates; Fig. 4) and their ability to remediate many waste products such as microplastics, excess nutrients and sewage, heavy metals, and many emerging or persistent pollutants is still scarce.

4. Conclusions

Despite the ongoing and increasing body of knowledge on impacts of OWF on biodiversity, the subsequent effects OWF have on ES is still facing policy limiting knowledge gaps and scientific uncertainties (Hooper et al., 2017a). Therefore, there is continuous need to build and synthesise currently available knowledge on both biodiversity and ES together to support decision making, particularly as OWF expand into new countries and marine environments. A summary of all available evidence from the reviewed literature ascertains that negative impacts on biodiversity and ES from OWF is prevalent overall (36%) but the presence of OWF may be beneficial (28%) or have no effect (27%) on existing biodiversity and local human community groups. This result with aligns other recent systematic reviews on the topic e.g. by Galparsoro et al. (2022) who also suggest OWF impacts on marine biodiversity components may be negative (in their case 72% of reported studies). The biodiversity impacts found in this study were generally negative on ES outcomes at the construction phase (52%), while more variable as well as potentially beneficial at the operational phase (34%), including supporting commercial fish and shellfish stocks, providing new habitat for key juvenile species, and providing areas for experiential recreation. A key finding is the differential susceptibility of different populations and species to impacts. Previous research (e.g., Papathanasopoulou et al., 2016) has reported generic impacts of OWF on high level taxonomic groups of species, for example on birds, reptiles or mammals, but this work indicates greater nuance and a need to place impacts into a population or species-level context to determine whether they are biologically significant, particularly when determining the overall ES impacts.

Overall, this study finds that there are 196 data gaps or unknown relationships (103 during construction and 94 during operation; total 86% unknown relationships) in the globally published peer-reviewed literature between OWF impacts, the biodiversity subject group and ES. This work demonstrates that more focused assessments of the implications of the OWF energy transition for biodiversity and ES are needed, including in: (i) emerging markets and southern hemisphere countries, particularly those with high future OWF potentials (e.g., Brazil, India, and Australia); (ii) on decommissioning of OWF and deeper-water floating structures; (iii) on several biotic groups including: elasmobranchs (e.g., sharks, skates, rays and sawfishes), marine reptiles (e.g., sea turtles), certain groups of marine mammals (e.g., whales, dugongs, sea lions), and other priority benthic habitats (e.g., tropical and cold water corals); and (iv) on the ES impacts of the construction stage and particularly those on regulating services. In many cases it is not clear how ecological changes, for example in fish abundance (3.2.1) and marine mammals' behaviour (3.2.3) will translate into changes in ES.

Additional evidence for the intensity and permanence of effects of OWF construction and operation on biodiversity and ES could also be produced, which are not yet well studied and are typically not addressed by the majority of the peer-reviewed literature. To implement this approach, more accurate data on the spatial distribution and temporal abundance of species during annual cycles as well as on the migration paths of fish, marine mammals, and birds around OWF would be required (Galparsoro et al., 2022), likely from 'direct' long term monitoring projects or from more 'indirect' dynamic ecosystem-model based approaches. In this study confidence in many of the subject groups, i.e. ecology (and subsequently ES) predictions are 'poor-moderate' primarily due to the limited number of studies available for evidence synthesis, and lack of studies beyond the individual OWF scale. Cumulative impacts on subject groups are also predicted to become increasingly important as the proportion of habitat occupied by OWF increases, but the magnitude and form of these effects on ES is currently highly uncertain (De Borger et al., 2021). Compensatory frameworks and measures for OWF effects on seabirds are under development in some countries, such as the UK and USA (Croll et al., 2022), and will become increasingly important in the future as cumulative effects of OWF developments become more acute.

Finally, whilst OWF developers, politicians, ecologists and economists are beginning to make progress towards 'net zero targets', decarbonization solutions and biocarbon offsetting (Fankhauser et al., 2022; Kaldellis and Apostolou, 2017), only four studies were available in this review to consider the globally important ES of carbon sequestration and storage in the context of deploying OWF. It is also clear that there is a wider global steer towards BNG approaches (Maron et al., 2018, 2020). As such, the ES impact matrix for example set out in Fig. 4 could set out a baseline from which new OWF developments could contribute towards marine biodiversity and ES net gain targets (Hooper et al., 2021), by potentially introducing pressure reduction measures to offset any negative ES impacts (e.g. reducing pile-driving noise during OWF construction or development), or compensatory measures that take advantage of enhanced opportunities involved with deploying OWF (for instance developing oyster reefs or restoring the seabed by prohibiting trawling fishing activities). Such approaches are likely to need the development of decision support tools and models that combine the environmental and socio-economic implications of offshore renewable energy developments, with frameworks for such evaluation approaches now becoming available (Causon et al., 2022; Trifonova et al., 2022). If implemented appropriately, these measures could deliver a win-win for sustainable energy development and enhancing marine biodiversity, including the ES and benefits they provide.

CRediT authorship contribution statement

Stephen C.L. Watson: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Paul J. Somerfield:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Anaëlle J. Lemasson:** Validation, Writing – review & editing. **Antony M. Knights:** Validation, Writing – review & editing, Funding acquisition. **Andrew Edwards-Jones:** Writing – review & editing. **Joana Nunes:** Writing – review & editing. **Christine Pascoe:** Writing – review & editing. **Caroline Louise McNeill:** Writing – review & editing. **Michaela Schratzberger:** Funding acquisition, Writing – review & editing. **Murray S.A. Thompson:** Writing – review & editing. **Elena Couce:** Writing – review & editing. **Claire L. Szostek:** Writing – review & editing. **Heather Baxter:** Writing – review & editing. **Nicola J. Beaumont:** Supervision, Visualization, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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