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Primary vs grey: A critical evaluation of literature sources used to assess the impacts of offshore wind farms

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ABSTRACT

The evidence-base for environmental and social impacts of offshore wind farms (OWF) is increasing with the exponential global growth of the offshore energy sector. In the UK, planning and consenting processes are lengthy (7+ years) and rely largely on evidence from grey literature sources. To meet 2030 and 2050 renewable energy targets and marine net gain ambition, policy and decision makers require access to the best available data. Translating environmental impacts into ecosystem services (ES) provides a qualitative framework by which to evaluate positive and negative outcomes. We review and synthesise UK grey literature (2012–2022) relating to OWF impacts and compare reported ES outcomes with those from global primary literature (2002–2021). Grey literature portrays a largely negative (71%) view of ES outcomes and fails to represent many positive ES outcomes reported in primary literature. In primary literature, 28% of reported ES outcomes are positive, but in UK grey literature this is just 2%. Evidence gaps are highlighted for both literature types, with major gaps for decommissioning outcomes, and sparse evidence for Provisioning ES (8%), Regulating ES (7%) and specific operational pressures. We recommend evidence from both literature types is used to achieve environmentally sound decision making and expedite planning and consenting times.

1. Introduction

The path from translating evidence into sensible and informed policy decisions involves the production, synthesis and evaluation of data. Policy and planning decisions are based on ecological and socio-economic evidence which is often obtained from grey rather than primary literature sources. Primary literature (PL) addresses specific research questions, is often (although not always) produced through research institutions and typically funded through research grants. Grey literature (GL) refers to multiple types of report or document, and is defined as: "information produced on all levels of government, academia, business and industry in electronic and print formats not controlled by commercial publishing" i.e. where publishing is not the primary activity of the producing body (ICGL, 1997). The purpose, objectives and processes involved in producing PL and GL are distinct. Benefits of GL include: providing an outlet for research where results are null or negative (and therefore less appealing to commercial publishers) (Paez, 2017); enabling new information to be circulated in a timely manner (formal publication can be a lengthy process); providing content from a diverse range of authors and sources; and accessibility (negates expensive journal subscriptions). However, drawbacks of GL are that due to the lack of a formal pre-publication review process, it can vary widely in quality, with potential for issues with rigor, transparency or impartiality. Environmental Impact Assessments (EIAs) (or Environmental Statements) and Habitat Risk Assessments (HRAs) are required for large infrastructure developments in the UK, including OWF and therefore contribute a large proportion of UK GL. This includes industry contracted research and non-peer-reviewed sources. This type of evidence is favoured by policy- and decision makers when evaluating environmental impacts of man-made structures in the sea (stw; pers. comm.). Excluding GL from meta-analyses can introduce bias and threaten the validity of findings (McAuley et al., 2000) and including GL has been advocated by the Centre for Environmental Evidence (CEE), as well as many researchers in the field of evidence synthesis (Haddaway and Bayliss, 2015). However, EIAs are designed around reporting negative impacts, which compromises the ability to take an integrated systems-based approach and include positive and non-local benefits (Causon et al., 2022).

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1.1. Environmental evidence for offshore energy expansion

We are in a period of significant growth for the global wind energy market (GWEC, 2023). To meet Global Net Zero emission targets by 2050, it is estimated that 2000 GW of offshore wind farms (OWF) will need to be installed worldwide, up from 35 GW in 2020 (GWEC, 2023). It is predicted global offshore wind capacity will hit the milestone of 1 TW in 2023, driven by a need to decrease carbon emissions and reduce reliance on fossil fuels. It could take just 7 years to double this capacity, with current projections (GWEC, 2023). This sector growth is also important to achieving the United Nations Sustainable Development Goal (SDG) 7; Affordable and Clean Energy (UN, 2016). Yet, despite this rapid expansion, uncertainty about the potential net effects of OWF developments can cause substantial delays during the planning and consenting process for developers. In addition to this, there are inconsistencies in evidence gathering and a lack of understanding of cumulative impacts (Willsteed et al., 2018). This can lead to regulators taking a precautionary approach to consenting new developments. Understanding environmental, social and economic outcomes associated with OWF compared to other energy systems is a key policy and evidence need and will aid in future energy policy and planning decisions.

1.2. OWF and marine ecosystem services (ES)

Ecosystem Services (ES) are defined as "the direct and indirect contributions that ecosystems provide for human wellbeing and quality of life", for example water, construction materials, energy, food or genetic resources. Ecosystem services are grouped into categories: Provisioning, Cultural, Regulating (Common International Classification of Ecosystem Services, CICES). A further category of Supporting ES is included in other classification frameworks (e.g. Millenium Ecosystem Assessment, MEA). By mapping biophysical resources or processes onto ES, it turns the approach from a broad concept into an operational tool for impact assessment. This moves beyond the EIA approach (which focusses on negative impacts), by integrating the socio-ecological aspects of the whole system. Tangible benefits to applying an ES framework are: (1) the approach allows impacts to be reported in a single metric, in language that can be understood by policy and decision makers, (2) both positive and negative outcomes can be evaluated, (3) it provides the foundation for monetary evaluation of natural capital and ecosystem services, (4) and enables cost/benefits and trade-off analyses to assess how ES can be enhanced or degraded by developments (Baulaz et al., 2023).

1.3. Aims and objectives

The UK currently lacks a defined, transparent process for communicating new evidence regarding the impacts of OWF to policy makers and regulators (owic.org.uk, 2023). It is also recognised that there is no standard approach to gathering or reporting such data, including monitoring data, which can lead to uncertainty in understanding potential impacts. A more robust evidence base is required to ensure that sound decisions are made under the 25 Year Plan (HM Government, 2018) and the Environmental Improvement Plan (HM Government, 2023). At present, decisions are predominantly based on evidence from GL, but could this be omitting vital information from the rapidly expanding PL (Galpasoro et al., 2022)?

We investigate this question with four main objectives: (1) Undertake a novel synthesis of UK GL relating to the environmental outcomes of OWF developments (2) Assign ES outcomes to the evidence to enable evaluation of trade-offs, (3) Compare and evaluate the quantity, type and direction (positive or negative) of ES outcomes reported, (4) Highlight data gaps and differences between PL and GL evidence to examine whether they provide different conclusions for the impacts of OWF, and enable policy and decision-makers to decide on the most appropriate evidence to use. An additional output of this study is a comprehensive, open-access evidence base for the environmental and socio-cultural impacts of OWF development from global primary and UK GL.

2. Methods

A semi-systematic review was undertaken for GL produced in the UK relating to the environmental and socio-cultural outcomes of OWF, building on an earlier review and synthesis of global PL on the same topic (Watson et al., 2024). Attempts were made to use the same search criteria as in the PL search but where search functions were either not available or did not have the capability to support Boolean searching, a manual search was performed. Manual searches used consistent search terms wherever this was possible/practicable within search engines. The terms used are on the 'Search terms' tab of the open-access database (S1) and a list of GL sources are on the 'Grey literature sources' table In total, 1776 documents were screened and 56 met the inclusion criteria (S2). Included reports were published between June 2012 and June 2022, with evidence applying to wind farms in UK waters. Rejected reports included pre-construction surveys, datasets, geotechnical and engineering reports, assessments of threats without interpretation of impacts, more detailed assessments of themes already summarised within broader non-technical reports, and any other outputs that did not indicate impacts on any ES. Impacts were classified in 20 categories (see S1 or Table 1 for examples). Data was extracted for each subject or marine ecosystem component that was impacted by the OWF development, the phase of development, the specific pressure and other relevant information about the wind farm or location (S3). Here, a piece of evidence is defined as a result from a scientific paper or grey literature report that links a cause (e.g. an action or effect arising from the construction, operation or decommissioning of an offshore wind farm or related infrastructure), and an observed impact on a species or community, physical process or cultural aspect of the marine environment. Multiple pieces of evidence may arise from a single report or scientific paper.

Following the methodology developed in Papathanasopoulou et al. (2015), Hooper et al. (2017) and Watson et al. (2024), expert judgement was used to map each piece of evidence for impacts on the marine environment according to CICES v5.1 for provisioning, regulating and cultural services or MEA framework for supporting services. Other published classification systems for ES were also used for the cultural services of 'sense of place' and 'social acceptance' (Ryfield et al., 2019; Hooper et al., 2020). The direction of each outcome was reported as positive, negative, no impact or inconclusive.

Outcomes relating to species or community abundance were classified as the Supporting ES of biodiversity, except when in relation to commercial fish species (classified as Provisioning ES), or abundance of

Table 1
Main ecosystem service categories, classification frameworks used and categories of evidence for impacts in the marine environment used in this study.

Ecosystem Service category	Classification framework	Example Outcome (e.g. an observed change based on effects or impacts of OWF)
Provisioning Services	CICES v5.1	Abundance, density or % cover of commercial species; financial gain or loss; community composition or structure
Regulating Services	CICES v5.1	Behaviour; reproductive output or fecundity; biomass or abundance of filter feeding organisms; sediment processes
Cultural Services	CICES v5.1; Ryfield et al. (2019); Hooper et al. (2020)	Visual amenities, the behaviour or abundance of charismatic marine species; attitudes or perceptions
Supporting Services	MEA	Species or community abundance, nutrient cycling, habitat quality; trophic structure

charismatic marine megafauna (classified as the existence and bequest aspect of Cultural ES). Outcomes relating to biomass or body size were classified as the Supporting ES of 'primary/secondary production'. Outcomes relating to condition or community structure were classified under the Supporting ES of life-cycle maintenance. Outcomes relating to habitat quality or condition were classified as the Supporting ES of 'Habitat'. Each piece of evidence was categorised as per Watson et al. (2024), with further categories added where necessary for the different types of evidence presented in the GL (S1). ES outcomes were linked to the UK descriptors of Good Environmental Status (GES) (DEFRA, 2019), or the UN Sustainable Development Goals (SDG's) (United Nations, 2016).

2.1. Analysis

Trends and patterns in ES outcomes and the direction of outcomes (positive, negative, no impact or inconclusive) were investigated. Differences between literature types were explored and tested for significance using Chi-squared tests where possible. Where there are too few data points for statistical analysis, observed trends are described.

3. Results

3.1. Overview of evidence sources and outcomes

The semi-systematic review process provided 56 UK GL reports with 755 pieces of evidence relating to ES outcomes from studies conducted between 2012–2022 (full database of extracted evidence in S1 and published here https://doi.org/10.5286/ukerc.edc.000961). Evidence from the GL relates to OWF in the UK, and in adjacent waters (North Sea, Irish Sea). In contrast there are more global primary studies (132) providing fewer pieces of evidence (319) from studies conducted between 2002–2020 Watson et al. (2024) (Table 1). There are 32 PL studies relating to waters around the British Isles.

In PL, positive ES outcomes represent 28% of the evidence, while just 2% of ES outcomes in UK GL are positive. In PL, 36% of ES outcomes are negative, while GL is heavily weighted towards negative ES outcomes (71%). There is a significant difference between the direction of ES outcome between GL and PL ($Chi^2 = 212.94$, d.f. = 3, $p < 0.001$). The proportion of inconclusive/no impact outcomes are fairly similar across PL and GL. When PL for the UK and adjacent waters is considered in isolation, the ratio of positive, negative and no impact/inconclusive outcomes are very similar to when all (global) PL is considered. However, outcomes from UK PL are weighted towards Cultural ES (77%) (Table 1).

3.2. Types of study

In PL, the majority of evidence comes from empirical or observational studies, followed by social studies, modelling and a limited number of laboratory experiments and literature-based assessments (Fig. 1). In contrast, the majority of evidence comes from literature-based assessments in GL (such as reviews, reports, consultation documents, environmental statements, HRAs), followed by empirical or observational studies, modelling and just two pieces of evidence from social studies. Although, the authors note that EIAs are based on mixed-methods assessments and may include data from empirical or modelling studies. In PL, empirical social studies (choice experiments, opinion surveys, questionnaires, interviews) provide data on socio-cultural outcomes. In GL, socio-cultural ES outcomes are established through literature-based assessments, working groups, scoping studies, visual impact assessments, archaeological/cultural assessment and socio-economic assessment.

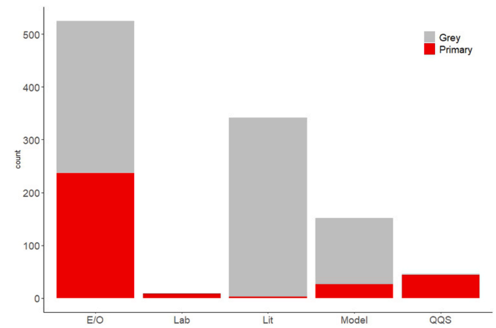

Fig. 1. Number of GL and PL studies relating to five different study types; E/O – empirical or observational; Lab – Laboratory experiment; Lit – Literature-based assessment; Model – modelling study; QQS – qualitative or quantitative social study.

3.3. Evidence by subject

There is a significant difference between the number of outcomes reported per subject group (biotic, abiotic, human/social) between GL and PL ($Chi^2 = 6.752$, d.f.=2, $p = 0.034$) (Fig. 2). In PL, there is most evidence for fish (n = 95), birds (n = 68), and invertebrates (n = 57) for construction and operational phases. In the construction phase, outcomes are also reported for marine mammals (n = 20) and humans (n = 1). In the operational phase, outcomes are also reported for humans (n = 45), with limited evidence for marine mammals, rock/sediment and meteorology.

The most reported subject in the GL was birds, across all wind farm phases; with outcomes reported for construction and operation (n = 273) and decommissioning (n = 47) (Fig. 3). Fish are the second most reported subject group in the construction and operational phase (n = 90), with outcomes for marine mammals third most reported (n = 89). For decommissioning outcomes in the GL, the 2nd and 3rd most frequently reported outcomes are for humans (n = 26) and marine mammals (n = 23). Habitat was added as a category for the GL, as many reported outcomes use this term, without providing specific detail. Across both literature types, there is sparse evidence for impacts on algae (n = 1) and coastal vegetation (n = 5). Water column effects (n = 17) are reported only in the GL (Fig. 3).

3.4. Evidence by operational phase

Across PL and GL, the majority of outcomes are reported for the presence of a wind farm, referred to as the 'operational' phase (74% and 49% respectively), with less evidence for the construction phase (26% and 32% respectively) (Table 1). There is a significant difference in the number of ES outcomes reported in each operational phase between GL and PL ($Chi^2 = 88.788$, d.f. = 2, $p < 0.001$). The majority (50%) of evidence from GL refers to the operational phase, with the remaining split between construction (30%) and decommissioning (20%) stages.

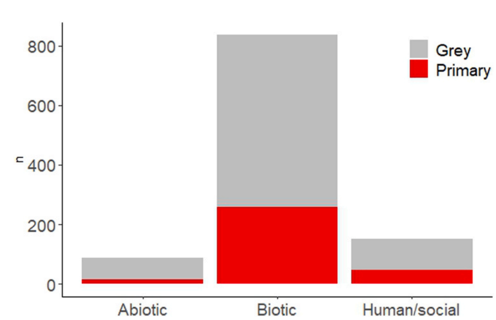

Fig. 2. Total pieces of evidence on the environmental outcomes of OWF from global PL (red bars) and UK GL (grey bars) literature, by subject group.

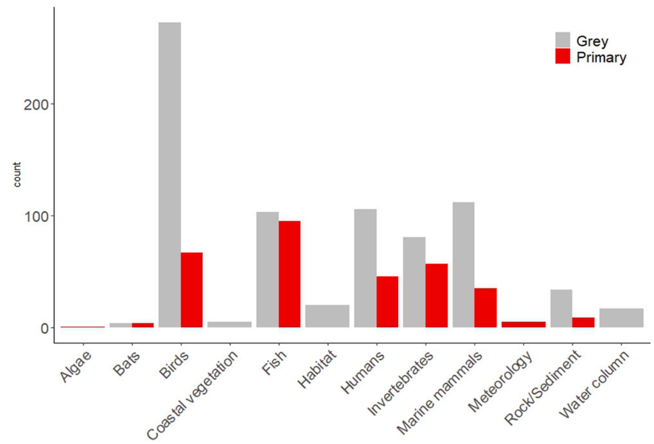

Fig. 3. Total pieces of evidence on the environmental outcomes of OWF from global PL (red bars) and UK GL (grey bars) literature, by subject.

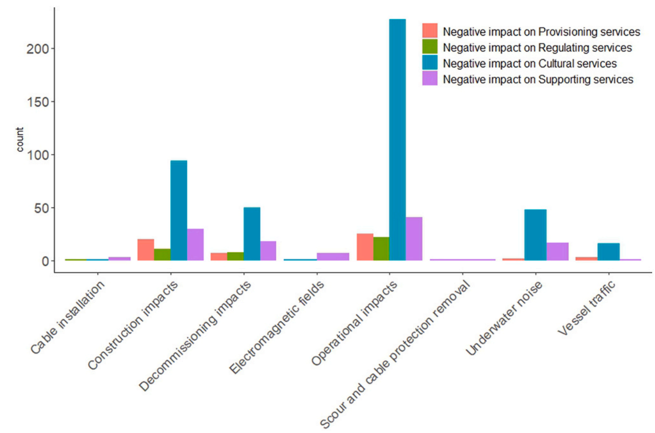

Fig. 5. Total pieces of evidence for negative ecosystem services outcomes of OWF, by pressure. Includes all outcomes reported from global PL and UK GL. count.

Evidence from PL relates to construction (26%) and operational (74%) phases only. The majority of construction phase ES outcomes reported in PL and GL are negative (52% and 72% respectively).

In the operational phase, negative impacts are reported in GL much more frequently (68%) than in PL (30%). There is most evidence for positive ES in the operational phase, largely relating to Cultural and Regulating ES (Fig. 4). For decommissioning, there is no evidence for ES outcomes in PL, and evidence in GL is weighted towards negative outcomes (78%). However, all the reported outcomes are inferred to be the same as for the construction and operational phases, and are not based on empirical evidence. Specific pressures that are reported to cause negative ES outcomes are general construction, operational and decommissioning activities, cable installation, electromagnetic fields, scour and cable protection removal, underwater noise and vessel traffic (Fig. 5).

3.5. Ecosystem service outcomes

The majority of evidence from both PL and GL in relation to the impacts of OWF relates to Cultural ES at 46% and 65% respectively (Table 1). All outcomes relating to marine megafauna were recorded under this service, as well as socio-cultural outcomes such as 'impact on seascape'. There is limited evidence for Provisioning ES in both types of literature (≤10% of all evidence) and Regulating ES (<8%). Supporting ES, including biodiversity related outcomes are better represented in PL (36%) than GL (20%). The net direction of outcomes for all ES across both types of literature is negative, except for the evidence for Regulating and Supporting ES in PL, where the net direction of outcomes is positive (furthermore, there are a proportionately high number of 'no impact' outcomes for Supporting ES) (Fig. 6). Detailed ES outcomes split by literature type are described in Table 2.

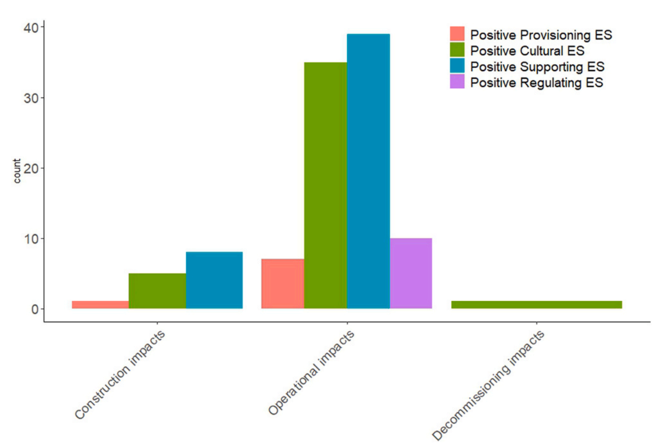

Fig. 4. Total pieces of evidence for positive ecosystem services outcomes of OWF, by operational phase. Includes all outcomes reported from global PL and UK GL.

3.6. No impact/inconclusive ES outcomes

For both PL and GL, around one quarter of all evidence reported no impact on ES. In PL, there is evidence for 'no impact' on Provisioning (n = 10), Regulating (n = 2), Cultural ES (n = 28) and Supporting ES (n = 46). In UK GL there are a similar number of 'no impact' evidence pieces for Provisioning (n = 14) and Regulating ES (n = 21), Cultural ES (n = 96) and Supporting ES (n = 48). Overall, 9% of ES outcomes in PL are inconclusive and 3% in GL. In PL, there are inconclusive outcomes for Regulating ES (n = 2), Cultural ES (n = 18) and Supporting ES (n = 8). In UK GL there are inconclusive outcomes for Provisioning ES (n = 2), Regulating ES (n = 1) and Cultural ES (n = 15) and Supporting ES (n = 2). Therefore, the greatest uncertainty in ES outcomes lies in Cultural ES, mainly in relation to impacts on marine megafauna and to a lesser extent on the social acceptance of OWF.

3.7. Relevance to UN sustainable development goals

ES outcomes mapped onto six of the 11 UK GES descriptors. Most outcomes related to D1 Biodiversity (n = 714, Table 3), followed by D3

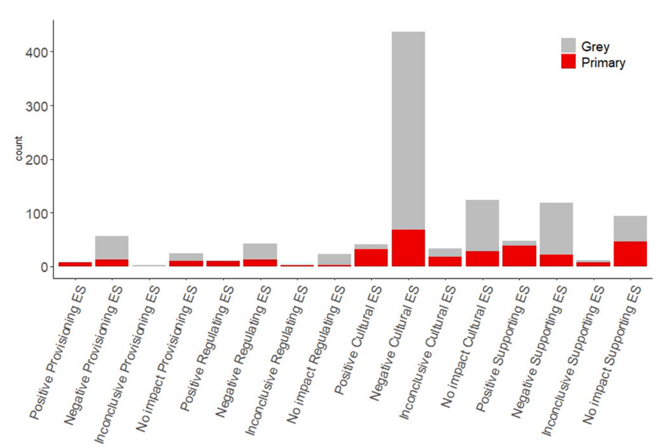

Fig. 6. Total pieces of evidence for the four ecosystem services, by outcome direction, split by PL (red) and GL (grey) literature.

Table 2
Comparison of total pieces of evidence from grey literature (GL) and primary literature (PL) relating to the environmental impacts and ES outcomes of OWF.

	Primary Literature - all	Primary Literature - UK	Grey Literature – UK only
Geographical range	UK & Global	UK	UK and adjacent waters
Time period	2002-2021	2012-2022	2012-2022
Studies meeting criteria	132	32	56
Total pieces of evidence	319	65	755
Positive ES outcomes | %	89 | 28%	14 | 22%	17 | 2%
Negative ES outcomes | %	116 | 36%	26 | 40%	538 | 71%
No impact outcomes | %	86 | 27%	19 | 29%	179 | 24%
Inconclusive outcomes | %	28 | 9%	6 | 9%	21 | 3%
Evidence for Provisioning ES | %	31 | 10%	5 | 8%	60 | 8%
Evidence for Regulating ES | %	27 | 8%	3 | 5%	51 | 7%
Evidence for Cultural ES | %	146 | 46%	50 | 77%	489 | 65%
Evidence for Supporting ES | %	115 | 36%	7 | 10%	155 | 20%
Construction phase	82 | 26%	242 | 32%	242 | 32%
Operational phase	237 | 74%	370 | 49%	370 | 49%
Decommissioning phase	0	143 | 19%	143 | 19%

Commercial fish and shellfish (n = 109). Other GES descriptors represented in the evidence are D6 Seafloor integrity, D7 Hydrological conditions, D11 Energy and noise and D2 Non-indigenous species. Cultural ES related to socio-cultural outcomes were mapped onto the UN Sustainable Development Goal 3 Health & Wellbeing, while 38 outcomes relating to archaeological features, heritage assets or seascape did not map onto any GES descriptors or SDGs.

4. Discussion

In this study we synthesise UK GL and compare it to global PL as an evidence-base for environmental decision-making in OWF developments. In line with the 2050 target to be carbon neutral (Net Zero) and meeting the UK Government 2030 50 GW offshore wind target (enough to power every home in the UK), a significant increase (25%) in the pace of deployment of OWFs is required. In the UK, development and deployment of OWF can take up to 13 years (Crown Estate, 2022). New policy objectives are to half this timescale for new offshore wind projects by 2023, and reduce consenting time to one year. It is clear that robust, peer-reviewed evidence from both PL and GL can play an essential part in this process. Transferring available evidence into ES language will aid in delivering positive actions to support protected habitats or species and evaluating trade-offs to achieve marine net gain (MNG), avoid the damage or loss of important habitats (Lloret et al., 2022) and help to streamline consenting processes.

4.1. Comparison of ES outcomes

A quarter of all evidence (from both PL and GL) indicates no impact on ES. These outcomes reflect parts of the development process that should be monitored but could remain neutral in the pursuance of MNG, which aims to put the marine environment into recovery by requiring that all in-scope developments leave the environment in a better state than before. Overall, evidence is weighted towards negative ES outcomes in relation to OWF in both PL and GL for each ES, with two exceptions; the net direction of outcomes for Supporting and Regulating ES

Table 3
Detailed ES outcomes split by high level ES and literature type (PL = primary literature; GL = grey literature).

ES category and Literature type	Positive outcomes	Negative outcomes
Provisioning ES – PL	n = 8; related to abundance, or catch per unit effort of commercial fish or shellfish species	n = 13; biomass for the provision of nutrition (abundance or catch per unit effort of commercial fish and shellfish)
Provisioning ES – GL	n = 0	n = 44; access to wild food for nutrition, access to wild animals for materials or energy
Regulating ES – PL	n = 45; life-cycle maintenance, waste remediation, climate regulation, carbon sequestration, regulation of physical, chemical, biological conditions, regulation of climate and extreme events	n = 34; pest and disease control, mediation of sediment flows, regulation of physical, chemical, biological conditions
Regulating ES - GL	n = 4; regulation of physical, chemical, biological conditions, maintaining nursery populations and habitats	n = 47; control of erosion, regulation of baseline flows, chemical condition of saltwater, nursery populations and habitats, regulation of physical, chemical, biological conditions
Cultural ES – PL	n = 32; public acceptance of OWF, aesthetic or physical interactions with OWF, existence and bequest values	n = 68; charismatic marine megafauna, experiential, existence and bequest aspects of cultural services, sense of place and identity, public acceptance of OWF and the physical, aesthetic enjoyment of the marine environment
Cultural ES – GL	n = 9; existence and bequest aspects, aspects of culture or heritage	n = 369; charismatic megafauna (n = 313), socio-cultural impacts (including commercial fisheries, tourism, heritage or archaeological features
Supporting ES – PL	n = 4; improved habitat quality and nutrient cycling (denitrification), biodiversity	n = 1; habitat quality
Supporting ES - GL	n = 4; biodiversity	n = 78; biodiversity

from PL is positive. The positive outcomes reported for Supporting ES in PL relate to nutrient cycling, habitat condition and biodiversity, but negative Supporting ES outcomes far outweigh positive outcomes in UK GL. This evidence requires careful analysis to ensure that Supporting ES trade-offs are balanced in favour of positive outcomes. Just eight pieces of positive evidence in UK GL relate to the supporting ES of biodiversity, although this may be due to the high proportion of EIAs in the evidence base that do not promote environmental benefits of developments. Negative Supporting ES outcomes in the GL relate to impacts on habitat quantity/quality and biodiversity, both of which could potentially be mitigated through environmental compensation schemes. Although Supporting ES are not represented in the CICES framework, they incorporate the important ecosystem services of biodiversity, nutrient cycling and habitat condition. These services are required to maintain healthy ecosystems and should be included in priorities for future research. Overall, the somewhat limited amount of evidence for positive Supporting ES reflects a barrier to the achievement of MNG goals. We demonstrate that evidence from PL provides some optimism and a basis for development of MNG approaches. The authors note that although the most appropriate ES was assigned, secondary ES may be applicable to each outcome.

Although Cultural ES are the second most abundant positive outcome in PL, both types of literature report a proportionally high number of negative outcomes for Cultural ES, and GL is heavily weighted towards negative Cultural ES outcomes overall. This is linked to the focus on high priority species such as birds and marine mammals in EIAs. The majority of Cultural ES for both PL and GL relate to biotic outcomes (for marine megafauna) (n = 514), with other outcomes for aesthetic or physical/experiential interactions with OWF. The majority of inconclusive outcomes are reported for Cultural ES, which suggests that either more in-depth research is required, or that impacts on marine fauna are potentially more complex than present evidence supports. Evidence relating to public opinion is also subject to change as the pace and frequency of OWF developments increases (Bingaman et al., 2023). Social acceptance is a key priority in marine spatial planning but UK GL does not reflect the positive public acceptance of OWF and positive interactions with the seascape that is apparent in a number of PL studies. Outcomes reported in GL are generic to seascape/heritage etc, rather than for individual opinion. Therefore, assessments could benefit from the use of PL social studies which are weighted in favour of positive outcomes.

Provisioning and Regulating ES are not well represented in either literature type. PL reports positive outcomes for a number of Regulating ES that are not reflected in UK GL, again indicating lost opportunities to recognise ecological benefits of OWF. Negative Regulating ES outcomes in the PL relate to pest and disease control, and mediation of mass flow, while a broader range of negative regulating ES outcomes are evidenced in the GL. Regulating ES regarding water column effects are not well represented in PL and this should be a research focus going forward. The presence of offshore wind turbines can reduce wind speed on the lee side of turbines and cause wave energy loss (Christensen et al., 2014), which could have multiple knock-on effects on water mixing and quality. Such impacts are being investigated under the multi-disciplinary PELAgIO-ECOWind project (https://ecowind.uk/projects/pelagio/), which is assessing impacts on water flow and mixing around turbine structures. Improved evidence for Regulating ES in the construction phase will aid in our understanding of the disturbance and release of sediments, carbon, nutrients, metals and plastics during construction.

There are <u>no</u> positive outcomes for Provisioning ES in the GL and just eight in PL relating to biomass for the provision of food or materials. Fisheries for pelagic fish species could contribute to the goal of achieving Net Zero carbon emissions, due to the relatively low carbon emissions compared with terrestrial protein or demersal or shellfish species, with fuel use the highest contributor to carbon emissions in the life-cycle analysis of fishing (Sandison et al., 2021). There is evidence to show that certain fish species aggregate at OWF, however it is difficult to ascertain whether this is simply a redistribution of the existing population, or whether OWF can lead to an increase in production (Reubens et al., 2014). Some studies report an increase in fish biomass or catch per unit effort (CPUE) near turbines (Reubens et al., 2014; Bergström et al., 2013) but outcomes are species specific and there are multiple pieces of evidence for a decrease in fish biomass or CPUE (Griffin et al., 2016). Outcomes may represent aggregation, migration of individuals or short-term effects (van Deurs et al., 2012). The lack of evidence for positive Provisioning ES could mean that this is a trade-off that will need to be made when considering new developments, or that a greater understanding of the impacts on different fish species, and the commercial fisheries such populations support, is required.

4.2. Outcomes related to GES/SDG

Linking ES to SDGs and GES enables evaluation of scenarios that yield the most positive outcomes in terms of achieving such goals (Ward et al., 2018). Prioritisation of SDGs differs between countries, therefore implementing ES-based solutions provides a mechanism to assess trade-offs between achieving environmental protection and human wellbeing (Yang et al., 2020). The majority of evidence for the impacts of OWF relate primarily to species and biodiversity, which provides an evidence base for the 'D1 Biodiversity' GES descriptor (Table 4). There is a reasonable amount of evidence for 'D3 Commercial fish and shellfish', although a better understanding of cumulative impacts on fish species and the fishing industry is needed. Outcomes relating to public acceptance of OWF and Cultural ES of interactions with the natural environment mapped on to the UN SDG 'Health & Wellbeing'. There is a reasonable amount of evidence (n = 83) in both PL and GL, but opinions vary by location and demographics and all new developments should be addressed with relevant studies (Reilly et al., 2015; Bingaman et al., 2023). Evidence relating to other GES descriptors is more limited; D6 seafloor integrity (n = 63), D11 Energy and noise (n = 33), D7 Hydrological conditions (n = 24), and D2 Non-indigenous species (n = 10) (Table 4).

4.3. Differences between primary & grey literature

The significant quantity of evidence found in GL *c.f.* PL is attributed to GL often reporting synthesised outcomes for a suite of subjects and impacts, whereas PL tends to have a narrower research focus, on a single topic or taxa. Multiple reports are required for each wind farm development at various stages of the consenting, developing and operational stages. Most evidence is available for the operational phase of an OWF, around twice the amount available for the construction phase, with the construction phase lacking focus in PL. This could be due to the logistical complications of sampling during construction or suggests that closer links are required between scientists and industry to fill this gap. There is a significant data gap for decommissioning impacts of OWF, with no evidence available in PL (Lemasson et al., 2022; Watson et al., 2024). Ecosystem service outcomes for the decommissioning phase reported in UK GL are mostly negative (78%). However, the outcomes are based on assumptions (that decommissioning outcomes are the same as for construction) and inference, rather than empirical evidence. Therefore, the reliability of the evidence should be considered speculative at best. This is a critical evidence gap that needs to be urgently addressed, as fixed wind turbines currently in operation have a lifespan of approximately 20 years and there is a lack of consensus on what the optimal decommissioning strategies would be (Edwards-Jones et al., 2024). There is an increased call for decommissioning options other than full removal of structures, and some recent evidence supports abandonment (Edwards-Jones et al., 2024; Knights et al., 2024). The prevalence of positive evidence from PL *c.f.* GL suggests decision makers and developers are potentially failing to account for many potential positive ES benefits that could result from OWF. Including evidence from PL could also enhance benefits to ES and contribute to MNG targets.

The much higher proportion of negative ES outcomes reported in the GL compared to PL are likely due to a range of factors. Research studies in PL typically investigate specific pressure/subject relationships, evaluated according to the statistical significance of the results which can be of a positive or negative direction. In many of the GL reports (e.g. EIAs and HRAs), only potential adverse effects are assessed, therefore omitting any positive outcomes that may occur as part of a development or activity. The direction of outcomes in EIAs are often summarised as either positive or negative, using terminology such as 'slight negative impact' or 'low to no significant impact', with no assessment of

Table 4
Number of ES outcomes relating to UK GES descriptors or UN SDGs.

Link to GES descriptor/UN SDG	n	%
D1 Biodiversity	714	66
D2 Non-indigenous species	10	1
D3 Commercial fish and shellfish	109	10
D6 Seafloor integrity	63	6
D7 Hydrological conditions	24	2
D11 Energy and noise	33	3
SDG 3 Health & Wellbeing	83	8
does not map	38	4

statistical significance, and little consideration for robust 'Before-After-Control-Impact' (BACI) experimental designs. Therefore, outcomes recorded as negative in the database might not reproduce significant impacts if tested empirically.

Grey literature comes from a wide array of sources such as governmental agencies, consultancies, industry and business (Lawrence et al., 2014). Such organisations may have mandates for resource management or conservation, and the strict process of peer review that is employed in the publishing of primary literature is mostly absent. While not typically indexed in citation databases, high-profile grey literature repositories exist (e.g. World Health Organization (WHO, https://www.who.int/publications/en/), the United Nations (https://digitallibrary.un.org) and the World Bank (http://www.worldbank.org/en/research/brief/publications), and grey literature is often referenced in articles and books (Bickley et al., 2020). In the UK, evidence statements that feed into decision making are formulated from both primary and grey literature, with confidence weightings attached to evidence sources (DEFRA, undated). This indicates the importance of evidence from grey literature in decision-making and information from grey literature plays an essential role in consultation processes that are characteristic of modern policy-making (MacDonald et al., 2015). Although GL reflects negative ES outcomes most frequently, the broader conclusion is often that those impacts are not significant enough to preclude construction. Where data is lacking or uncertainty dominates, decision makers may still have to take a precautionary approach, although this is likely to impede developments and timescales.

4.4. Evidence gaps

Although the proportion of inconclusive outcomes is low (9% and 3% in PL and GL respectively), this highlights areas where more research is needed. Subjects where data was inconclusive include commercial fish species, climate regulation and baseline flows, behavioural or population insights for marine megafauna, public acceptance of OWF, biodiversity and nutrient cycling. PL evidence relating to construction impacts focuses on larger fauna (e.g. birds, fish, mammals). Data regarding infauna and relating to regulating ES (water column effects, sedimentation, carbon storage/release etc) in the construction phase (including cable installation) is limited, but is necessary to ensure that all levels of the ecosystem are accounted for in planning. OWF can potentially contribute to localized vertical mixing, nutrient concentrations and primary production and can enhance benthic biomass through the provision of hard substrate (Rezaei et al., 2023). However, OWF can impact eutrophication, and regular monitoring of dissolved oxygen, phosphorous and chlorophyll-*a* concentrations should be maintained to avoid issues (Rezaei et al., 2023). While GL reports some abiotic outcomes for the construction phase (n = 26) this is largely from EIA reports and there is limited empirical evidence. Data on the impacts of decommissioning OWF, across all ES is urgently needed, as present evidence is based on inferred outcomes only.

The risk of cumulative adverse effects of OWF is poorly researched and assessment processes are underdeveloped (Willsteed et al., 2018). Recent developments have addressed potential cumulative impacts on marine birds (Goodale and Milman, 2016), and provide a framework for assessment including compensatory and mitigation measures (Croll et al., 2022). The expansion of non-natives through the stepping stone effect, as well as impacts on existing species' distributions and genetic population structure should also be considered (Adams et al., 2014). EIAs attempt to cover cumulative effects, although approaches are inconsistent.

Electro-magnetic field (EMF) effects have been found to alter the behaviour and migration of some fish and crustacean species (Rezaei et al., 2023). In relation to EMF outcomes, there are 13 pieces of empirical evidence from PL and 12 outcomes reported in GL, covering a range of taxonomic groups such as fish, crustaceans and polychaetes, but only a single study per taxa exists, which suggests more evidence is required to improve reliability. The effects of underwater noise (related to construction or operational activities) are addressed in the PL for porpoises, seals and crabs (n = 9), with outcomes for marine mammals thought to be the greatest, but this clearly omits a wide range of species and taxonomic groups. Outcomes include aversion and displacement, but there is some evidence for increased presence of marine mammals within turbine arrays (Scheidat et al., 2008). The noise from underwater pile-driving could also cause auditory damage in marine mammals (Brandt et al., 2011). There is more evidence in GL for underwater noise impacts (n = 90) from monitoring/observational and modelling studies. Vessel traffic impacts are only addressed by a single study in PL, while there are 22 pieces of evidence in UK GL. Impacts such as this need to be considered in cumulative impact assessments. Just a single piece of evidence from GL addresses the impacts of scour and cable protection removal and there is no evidence for cable installation impacts in PL, with just seven pieces of evidence in UK GL. Most of the available literature reports short-term impacts of OWF, while just one study presently assesses longer-term outcomes (Degraer et al., 2020). Outcomes observed in the short-term (such as increased abundance) may not persist over longer-term monitoring periods (Rezaei et al., 2023), therefore the development of consistent and robust long-term monitoring schemes are essential.

In addition to this, all current literature relates to fixed OWF structures which are located in fairly shallow water (> 15 miles from the coast). Currently, the deepest fixed base OWF is Seagreen, located about 27 km off the coast of Angus, Scotland at 59 m sea bed depth (Sea Green Wind Energy, 2023). With the planned increase in capacity and the development of floating wind farms, structures will be sited further offshore and in water up to 700 m depth (Díaz et al., 2022). Current evidence will not be adequate for the different habitats and communities impacted by floating OWF and priorities should lie in developing the evidence base for these types of installations. Key evidence gaps are summarised in Table 5.

4.5. Implications for policy and decision making

In this study, we reveal clear differences in both the direction and quantity of evidence for the four main ES (Provisioning, Regulating, Cultural and Supporting) in relation to the environmental and socio-cultural outcomes of OWF. We included GL from the UK, but other country or location specific investigations into GL may reveal further inequalities or diverging conclusions surrounding the outcomes of OWF. Developments of marine infrastructure and the associated disturbance to the natural environment will have an impact on ES; detailed knowledge of the benefits, drawbacks, data gaps and cumulative impacts is imperative to produce accurate impact assessments for sound environmental decisions.

Reasons why PL is not currently favoured in policy decisions are: (1) it can be difficult or expensive to access, (2) the time lag between research and publication (GL is immediately available), (3) historically

Table 5
Key evidence gaps for Ecosystem Service outcomes in relation to offshore fixed and floating wind developments.

Key evidence gaps
Construction phase (in particular Regulating ES)
Decommissioning phase - all ES
Cultural ES - inconclusive outcomes
Provisioning & Regulating ES
Underwater noise impacts (by species/taxa)
Cable installation
Vessel traffic impacts
Cumulative impacts
Floating OWF
GES D7 Hydrological conditions
GES D6 Seafloor integrity

it has been less common for developers to work directly with scientists, (4) reported outcomes can be too specific or in an unsuitable format for use in policy recommendations; GL can be more 'user-friendly' and often provides a summary of impacts and evidence.

There has been an exponential increase in PL relating to the ecological impacts of OWF in the last eight years (Galpasoro et al., 2022) and it is clear that decision making could be enhanced by including all available evidence. Failure to incorporate evidence from PL could slow or impede the planning and consenting process. It should be a priority for the scientific and regulatory communities to achieve and maintain open communication channels to provide the best possible evidence for decision making in a timely manner, to speed up the planning and consenting process, inform ES trade-offs and work towards achieving MNG. Robotics, AI and smart/autonomous technologies will also help to improve data gathering and speed up processes for consenting and environmental monitoring in the future (ORE Catapult, 2023) and such data must be made available at the earliest opportunity.

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CRediT authorship contribution statement

Beaumont Nicola J: Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Szostek Claire:** Data curation, Formal analysis, Investigation, Writing – original draft. **Watson Stephen C.L.:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – review & editing. **Edwards-Jones Andrew:** Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing.

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

The data is provided in supplementary material.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2024.103693.

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