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Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms

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ABSTRACT

The growing awareness of climate change and the recognised need to secure energy production has been a driving force behind the expansion of the offshore wind industry across the world. Benefits from offshore wind farms (OWFs) may extend further than low CO_2 energy production. Wind turbine substructures introduce hard surfaces that are rapidly colonised by epibenthic marine organisms, altering biomass and biodiversity within the local ecosystem. Biodiversity plays a critical role in supporting ecosystem processes and functions that maintain ecosystem services. As offshore wind development continues to grow and modify marine habitats, changes in biodiversity could affect the provision of ecosystem services. In this context, this review sets out to capture the current understanding of epibenthic biodiversity change following the installation of OWFs and attempt to link these changes in biodiversity with marine ecosystem services through the associated processes and functions.

1. Introduction

A growing awareness of the effects of climate change and concerns over energy security have been driving forces for renewable energy (Mangi, 2013; Szulecki et al., 2016; Voormolen et al., 2016). Owing to much larger installed turbines, as well as the stronger, more consistent winds offshore, offshore wind farms (OWFs) have a higher potential to harness renewable energy than their terrestrial counterparts (Petersen and Malm, 2006; Lange et al., 2010). As a result, the offshore wind energy industry has seen considerable investment. In European waters, the cumulative installed capacity of OWFs rose from 0.8 GW in 2006 to 12.6 GW by the end of 2016 (Corbetta and Miloradovic, 2016). The European offshore wind industry is expected to continue to expand and may contribute more than 10% of Europe's energy (around 140 GW) by 2030 (Zervos et al., 2009; Langhamer, 2012). Growth has been slower outside of Europe, but substantial expansion is still expected. Japan's cumulative installed offshore wind capacity was 59.6 MW by the end of 2016 with around 2.5 GW more in various stages of development (GWEC, 2016). In China and North America, offshore wind capacity is expected to achieve 5 GW (up from 1.6 GW in 2015) and 10 GW by 2020 respectively (GWEC, 2016; Zhao and Ren, 2015; Lü et al., 2017). That expansion is set to increase in North America to 54 GW by 2030 (Zhao and Ren, 2015).

Whilst it is largely accepted that OWFs provide net benefit to the global environment by reducing direct CO_2 emissions, it is not clear how large-scale installation of OWFs may influence local ecosystems. Modification of marine habitat following the installation of an OWF is expected to change local and regional biodiversity. Key ecosystem processes are supported by biodiversity, which are crucial to the delivery of multiple functions that affect the provision of ecosystem services (Wilhelmsson and Malm, 2008; Mace et al., 2012; Snelgrove et al., 2014). Ecosystem services are goods and benefits humans derive from nature, emphasised as components of wealth, well-being and sustainability (Mace et al., 2012; Carpenter and Turner, 2000; Liquete et al., 2013; Costanza et al., 2014). Identified as provisioning (e.g. food), regulating (e.g. carbon sequestration), cultural (e.g. tourism and recreation) and supporting (e.g. nutrient cycling) (Millennium Ecosystem Assessment, 2005; Beaumont et al., 2007); they are, in essence, by-products of ecosystem processes and functions that are recognised as being beneficial to people, particularly in relation to health and well-being (Sandifer et al., 2015). Such processes and functions are supported by biodiversity at local and regional scales.

It is generally considered that high biodiversity supports high ecosystem functionality, with declines in biodiversity having a negative effect on ecosystem functions (Loreau, 2001; Hooper et al., 2005; Balvanera et al., 2006; Cardinale et al., 2012; Lefcheck et al., 2015; Gamfeldt et al., 2015). For instance, ecosystems with high biodiversity typically have greater resistance to disturbance (Purvis and Hector,

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2000; Tilman et al., 2006; Isbell et al., 2015). Worm et al (Worm et al., 2006) support this observation; they demonstrated that lower rates of collapse and higher rates of recovery in commercially important fisheries occurred where there was higher regional species richness. It has been suggested that the presence of species with similar ecological roles and traits effectively provides biological redundancy and protects against changes to ecosystem function (Levin, 1999; Duarte, 2000; Palumbi et al., 2009). Thus, a reduction in species richness could result in an ecosystem that is less resilient. Whereas increased biomass and biodiversity due to introduced hard substrate may create resilience in epibenthic populations, which may further support higher trophic levels.

In recent decades, ecosystem services have become a major area of research, development and policy attention in terrestrial systems (Naidoo et al., 2008). In marine environments however, ecosystem services have received less attention, beyond fisheries and related industries (Liquete et al., 2013; Gee and Burkhard, 2010) and only recently have the effects of OWFs on the delivery of ecosystem services been studied (Mangi, 2013; Busch et al., 2011; Hattam et al., 2015; Wilding et al., 2017). However, linkages have not been made between biodiversity, ecosystem functions, and ecosystem services. With the evident expansion of offshore wind energy across the world there is a common need to consider how the associated large-scale habitat modification, through the installation of OWFs, and subsequent changes to biodiversity, could affect the provision of ecosystem services. Determining how changes in biodiversity would impact processes and functions is central to determining the effect of OWFs on the delivery of associated ecosystem services. As such, this review aims to specifically link changes to biodiversity, in relation to OWFs with ecosystem services through associated processes and functions.

2. Habitat modification by offshore wind farms

By introducing hard substrate in the form of the turbine towers, foundations, cables and scour protection, OWFs increase the complexity of the seabed and the water column and present opportunities for food and shelter for benthic associated organisms at various life stages (Petersen and Malm, 2006; Langhamer, 2012; Coates et al., 2011). Thus, in effect OWFs act as artificial reefs, increasing local biomass and promoting biodiversity (Mangi, 2013; Langhamer, 2012). This is not unexpected; hard substrate in the marine environment, such as OWFs and oil and gas platforms, have been shown to be rapidly and intensively colonised by epibenthic species (Connell and Slatyer, 1977; Kerckhof et al., 2009, 2010; Degraer et al., 2012; Kerckhof et al., 2012). Indeed, artificial structures, including shipwrecks, sea walls, oil and gas platforms and purpose built artificial reefs, have been shown to support diverse reef communities (Zintzen and Massin, 2010; Lengkeek et al., 2011; Schrieken et al., 2013; Lengkeek et al., 2013; Whomersley and Picken, 2003; Wolfson et al., 1979; Forteath et al., 1982; Guerin et al., 2007; Mallat et al., 2014). In the southern North Sea, up to 250 taxa have been recorded on shipwrecks, which was similar to the species richness recorded by soft substrate surveys of the entire Dutch continental shelf (Lengkeek et al., 2011; Schrieken et al., 2013; Daan and Mulder, 2006). In addition, fish species are known to aggregate around hard-structures largely due to the provision of food through the development of species rich epifauna-communities (Reubens et al., 2011; Svane and Petersen, 2001). Atlantic cod, *Gadus morhua*, have shown a preference for hard substrate habitats and it has been noted that close proximity to shipwrecks provides protection from bottom trawl fisheries (Lengkeek et al., 2013).

Fish, including commercial species, have been shown to aggregate around wind turbine foundations (Reubens et al., 2013, 2011), which may have added benefits for exploited populations. As offshore wind turbine foundations present a hazard to fishing gear they may, over time, encourage recovery of commercially exploited fish stocks and lead to over-spill to surrounding areas (Langhamer, 2012; Busch et al., 2011; Lengkeek et al., 2013). However, evidence of benefits of OWFs to fisheries have so far been inconclusive. In the North Sea, reported catches before and after the construction of Kentish Flats and North Hoyle wind farms showed no significant changes, although catch per unit effort (CPUE) from survey trawls within the Kentish flats wind farm were higher for all species except sole (Mangi, 2013).

Typically, wind turbines have been installed in regions characterised by a soft sandy benthic environment, such as the North Sea, where hard substrate and intertidal regions are uncommon (Hooper et al., 2015; Kerckhof et al., 2011; Mangi, 2013; Lengkeek et al., 2013). Therefore, OWFs represent a large-scale increase in local habitat heterogeneity that may lead to a regional shift from sediment associated benthic to hard bottom and intertidal communities (Kerckhof et al., 2011; Mangi, 2013; Lengkeek et al., 2013). Indeed, several studies have indicated that epifauna assemblages found on artificial reefs, including wind turbine piles, differ from those on nearby reefs and natural substrate (Connell and Glasby, 1999; Petersen and Malm, 2006). Moreover, there is evidence artificial reefs may act as stepping stones for non-native species (De Mesel et al., 2015; Gill, 2005; Glasby et al., 2007). Kerckhof et al (Kerckhof et al., 2011) demonstrated that OWFs in the Southern North Sea were rapidly colonised by non-indigenous species, particularly in the intertidal region.

The introduction of epibenthic assemblages can also modify the local hydrodynamic regime, biochemistry and benthic sediment composition (Boehlert and Gill, 2010; Coates et al., 2011; Miller et al., 2013; Vaissière et al., 2014). Hiscock et al (Hiscock et al., 2002) suggested that alteration of local hydrodynamic regimes may lead to turbulences that cause resuspension of fine sediments, reducing light penetration and smothering existing benthic communities.

There is concern around the potential for this large-scale reef effect to modify marine ecosystems (Petersen and Malm, 2006; Langhamer, 2012) as OWF developments introduce an significant hard substrate surface area to a previously open water and an often sedimentary sea bed habitat (Boehlert and Gill, 2010; Coates et al., 2011). To date, on European coastlines, more than 3500 turbines have been installed (Byrne et al., 2017). It is important to note that OWFs differ from other structures in that modification of the local environment spans multiple devices. Expressly, rather than a single large reef, an OWF represents a network of interconnected smaller artificial reefs. A single turbine has a relatively small ecological footprint. To illustrate, recent monopile designs have a diameter of 8 m (Byrne et al., 2017), leading to a footprint on the seabed of 50.3 m^2 (not including scour protection). Jacket foundations have a larger footprint. For example, a foundation with a base of 20 m (Seidel, 2007) would have a footprint of 400 m^2. However, this remains relatively small when compared with that of an OWF array, which may be several square kilometres with turbines separated by distances of 500–1000 m (Snyder and Kaiser, 2009). Many of the proposed larger developments with hundreds of turbines will have footprints of several hundred square kilometres (Boehlert and Gill, 2010; Gill, 2005).

Changes to the habitat on the scale of a single turbine may have minor effects in isolation, but cumulative effects across the scale of an OWF may be substantial and are, at present, highly uncertain (Willsteed et al., 2017). The level of complexity and variation would make scaling ecosystem services across OWFs and estimating cumulative impacts very challenging. There would be variations in local conditions, such as hydrodynamic regime. Additionally, the installation of OWFs span across seasons. As a result, the oceanographic conditions and species richness in the water column would vary between turbine installations. As such, it is likely that multiple stages of development may be seen on turbine substructures within a single OWF. Further, as with any natural reef, communities on turbine substructures will change and adapt over time. Therefore, it is not unreasonable to expect the delivery of ecosystem services to vary over the lifespan of turbines.

Based on existing evidence it is expected that the OWFs would dramatically change local biodiversity, and hence the associated

ecosystem processes and functions. It is important to understand the causes and effects that lead to these changes which manifest themselves in terms of their biological or ecological significance to truly determine the impact on the local environment. However, determination of the significance of the environmental impacts related to these changes are often not fully realised (Boehlert and Gill, 2010).

3. Offshore wind farms and benthic ecosystem dynamics

Epibenthic colonisation is a multistage process that begins at the microbial scale. Immediately following immersion dissolved macromolecules adhere to the substrate, forming a thin conditioning film (Cooksey and Wigglesworth-Cooksey, 1995; Melo and Bott, 1997; Qian et al., 2003; Dobretsov et al., 2006). Within hours bacteria attach to the adsorbed layer of organic material (Melo and Bott, 1997). These are followed by microscopic eukaryotes, such as diatoms, fungi and other heterotrophic eukaryotic organisms which, along with bacteria, begin to form biofilms (Dobretsov et al., 2006; Qian et al., 2007). The presence of biofilms has been described as a cue for colonisation, in that may encourage or deter larval and spore settlement (Qian et al., 2007; Dobretsov, 2010).

Colonisation is spatially dynamic, influenced not only by environmental variability but also structural characteristics of the substrate (De Mesel et al., 2015). It has long been understood that marine organisms occupy distinct bands above and below the waterline (Whomersley and Picken, 2003; Stephenson and Stephenson, 1949; Southward, 1958). This pattern of zonation is a result of localised environmental characteristics forming fine scale habitats. Similar patterns have been found on existing offshore structures, such as offshore oil and gas platforms where studies of epibenthic communities have described patterns of zonation in relation to depth (Wolfson et al., 1979; Forteath et al., 1982; Guerin et al., 2007; Mallat et al., 2014). Not unexpectedly, recent studies have also described zonation on offshore wind turbine foundations (De Mesel et al., 2015; Kerckhof et al., 2009).

Spatial orientation is considered a major determinant of heterogeneity in colonising communities (Bourget et al., 1994; Bulleri and Chapman, 2004; Glasby, 2000; Glasby and Connell, 2001; Moura et al., 2008). Indeed, epibenthic assemblages have been shown to differ with spatial orientation on natural rocky substrate and artificial surfaces, including panels, shipwrecks, pontoons, pilings, and oil and gas platforms (Connell and Glasby, 1999; Forteath et al., 1982; Fuller, 1946; RG and CH, 2001; Todd and Turner, 1986; Wendt et al., 1989; Baynes, 1999; Connell and Anderson, 1999). Moreover, there is evidence that some species preferentially settle, or have greater survival rates, on surfaces with particular orientation. Moura et al (Moura et al., 2008) found that on horizontal surfaces of experimental cubes the sessile epibenthic assemblages were dominated by cirripeds, predominantly *Amphibalanus amphitrite* (previously reported as *Balanus amphitrite* by Moura et al (Moura et al., 2008). Similarly, (Connell and Glasby, 1999) found that assemblages on vertical surfaces of pontoons differed from those attached to horizontal undersides (Connell, 1999). Several studies have also shown barnacles, bryozoans, and some sponges tend to be more abundant on suspended substrata, whereas algae are more dominant on fixed substrata (Glasby and Connell, 2001; Fuller, 1946; RG and CH, 2001).

Several wind turbine foundation designs are in commercial use, which vary in shape, size and materials. Variation in substratum characteristics between structures may create different initial conditions for biofilm development, which is likely to influence the subsequent stages of colonisation (De Mesel et al., 2015). Additionally, scour protection used around wind turbine foundations add complexity and provide further habitat.

Table 1 compares epibenthic communities found on a monopile and jacket substructure from published literature (Hiscock et al., 2002; Bouma, 2012; Krone et al., 2013). It should be noted, however, that structures included in these studies differed not only in foundation type but also age, location and installation season; factors that can also influence the development of epibenthic communities. Nonetheless the choice of foundation for turbines may create different opportunities for colonising organisms within an OWF. Indeed, greater complexity in jacket foundations, with structures in multiple orientations, as well as sheltered and shaded surfaces, is likely to provide a very different habitat from monopiles.

Floating turbines are an emerging technology that has not reached the commercial market. Empirical and monitoring data from colonising communities are absent. As such the illustration in Table 1 was produced using published data from buoys and deep water oil rigs (Forteath et al., 1982; Macleod et al., 2016; Southgate and Myers, 1985).

Although a floating spar may appear similar in shape to a monopile there are key differences in the habitat they create. As a floating structure that rises and falls with the tide, a spar would not introduce a true intertidal zone. Therefore, it is unlikely that substantial intertidal community would be present above the water line. Although there would be a splash zone and those species present would be able to survive long periods of desiccation. In addition, as the structure is not in contact with the benthos scour protection would not be required. Rather, the spar would be kept in place through moorings. However, mooring lines and the cables would also be colonised by epibenthic organisms.

Over a large OWF the foundation type could have important implications for habitat modification, which would affect biodiversity, ecosystem function, and subsequently the delivery of ecosystem services.

4. Biodiversity and ecosystem function

Maintaining marine ecosystem health and function is essential to underpin our planet's life support systems (Mangi, 2013). Multiple direct and indirect effects on ecosystem processes and functions are expected following OWF installation (Gill, 2005). These can be linked to the delivery of ecosystem services. Fig. 1 presents a conceptual schematic illustrating such relationships.

Direct effects include physical changes to the habitat from the installation of turbines and other structures. In Fig. 1, the blue dashed boxes on the left cover changes in hydrodynamic regime (Matutano et al., 2016), benthic habitat loss or gain and the provision of shelter from fishing and predation (Gill, 2005; Miller et al., 2013; Wilson and Elliott, 2009; Wilson et al., 2010).

Indirect effects, linked to the direct effects, include modification to processes and functions, and are shown by the series of boxes and arrows in the central, red section of Fig. 1. For example, complex epibenthic communities colonise turbine substructures forming artificial reefs (Table 1) which can alter biodiversity and community structure, influencing processes and functions (Hooper et al., 2005; Schleuning et al., 2015). This reef effect can be linked to ecosystem services through several channels, indicated by the green dashed boxes on the right of Fig. 1. For instance, littoral fall, which is the deposition of faecal and other organic matter by epibenthic organisms colonising the turbine substructure, may enrich sediments, supporting soft-sediment communities (Coates et al., 2011; Köller et al., 2006; Maar et al., 2009; Coates et al., 2014). Feeding and bioturbation by benthic infauna contributes to the transfer of organic matter in to sediments and influences the rates of remineralisation and inorganic nutrient efflux (Hansen and Kristensen, 1997; Christensen et al., 2000; Aller, 2017; Welsh, 2010; Kristensen, 2000; Lohrer et al., 2004). Inorganic matter returned to the water column by bioturbating organisms influences primary productivity. Coates et al (Coates et al., 2011) recorded higher Chlorophyll-a concentrations around a gravity based turbine than had been found in similar sandy-sediments. They noted that, in combination with a slight decrease in median grain size, increased productivity may enhance larval settlement and survival of certain macrobenthic species.

Table 1
Expected offshore wind turbine epibenthic community profiles for different turbine structure designs using examples from European seas based on published literature (Bouma, 2012; Hiscock et al., 2002; Krone et al., 2013). Dashed lines show depths at which communities' change.

Depth	Monopile		Jacket		Floating	
	Representative Taxa	Example Species from Europe	Representative Taxa	Example Species from Europe	Representative Taxa	Example Species from Europe
Intertidal/ Splash	Ephemeral algae	*Ulva lactuca and Ulva intestinalis*	Ephemeral algae	*Ulva lactuca* and *Ulva intestinalis*	Ephemeral algae	*Ulva intestinalis*
	Red foliose algae	*Porphyra* spp.				
	Barnacles	*Semibalanus balanoides and Austrominius modestus*	Barnacles	*Semibalanus balanoides* and *Austrominius modestus*	Red foliose algae	*Porphyra* spp.
	Oysters	Mainly *Crassostrea gigas,* but also *Ostrea edulis*				
0 metres	Mussels	*Mytilus edulis*	Mussels	*Mytilus edulis*	Ephemeral algae	*U. lactuca* and *U. intestinalis*
	Crustaceans	Unspecified				
	Anemones	Diadumene cincta and Metridium dianthus	Anthozoa	*Hexacorallia* spp.	Red algae	*Polysiphonia brodiei*
	Sponges	*Halichondria panicea*	Red algae	Unspecified		
5 metres	Hydroids	*Ectopleura larynx*			Red algae	*Polysiphonia stricta*
	Sea stars	*Asterias rubens*	Sea urchin	*Psammechinus miliaris*	Hydroid	*Ectopleura larynx* (associated with algal growth)
	Mussels	*M. edulis*			Crustacean	*Jassa falcata* (associated with algal growth)
			Sea star	*Asterias rubens* (low abundance)	Mussels	*Mytilus edulis*
10 metres	Crustaceans	Unspecified			Anemones	*Metridium dianthus* and *Sagartia troglodytes*
			Mussels	*M. edulis*	Mussels	*M. edulis*
	Anemones	M. dianthus, D cincta and Sagartia elegans (the latter two in lower abundance)	Anemones	*M. dianthus*		
15 metres	Soft corals	*Alcyonium digitatum*	*Hexacorallia*	Unspecified		
			Brittle stars	*Ophiothrix fragilis*		
	Hydroids	*Obelia* spp., *Kirchenpaueria pinnata* and *Tubularia indivisa*	Sea stars	*A. rubens*	Anemones	*M. dianthus* and *S. trolodytes*
			Crabs	*Cancer pagurus* and *Necora puber* (the latter below 15 metres)		
20 metres	Sponges	*Amphilectus fucorum*	Anemones	*M. dianthus*	Anemones	*M. dianthus* (20-80 metres with max abundance approx 25 metres)
	Solitary sea squirts	*Ascidiella* spp.				
25 metres	Sea stars	*A. rubens*	*Hexacorallia*	*Unspecified*	Serpulid worms	*Spirobranchus triqueter* (20-80 metres may be interspersed with *M. senile*) and *Hydroides norvegica* (below approx 50 metres)
			Crabs	*C. pagurus* and *N. puber* (the latter in low abundance)		
	Sea urchins	*Psammechinus miliaris*			Soft corals	*Alcyonium digitatum* (particularly between 20-30 metres)
Scour protection / > 30 metres	Serpulid worms	*Spirobranchus triqueter*	Mussels	*M. edulis*		
	Barnacles	*Balanus crenatus*				
	Bryozoa	Encrusting sea mats Large patches of bare substrate	Brittle stars	*O. fragilis*	Barnacles	*Chirona hameri* (below 75 metres)

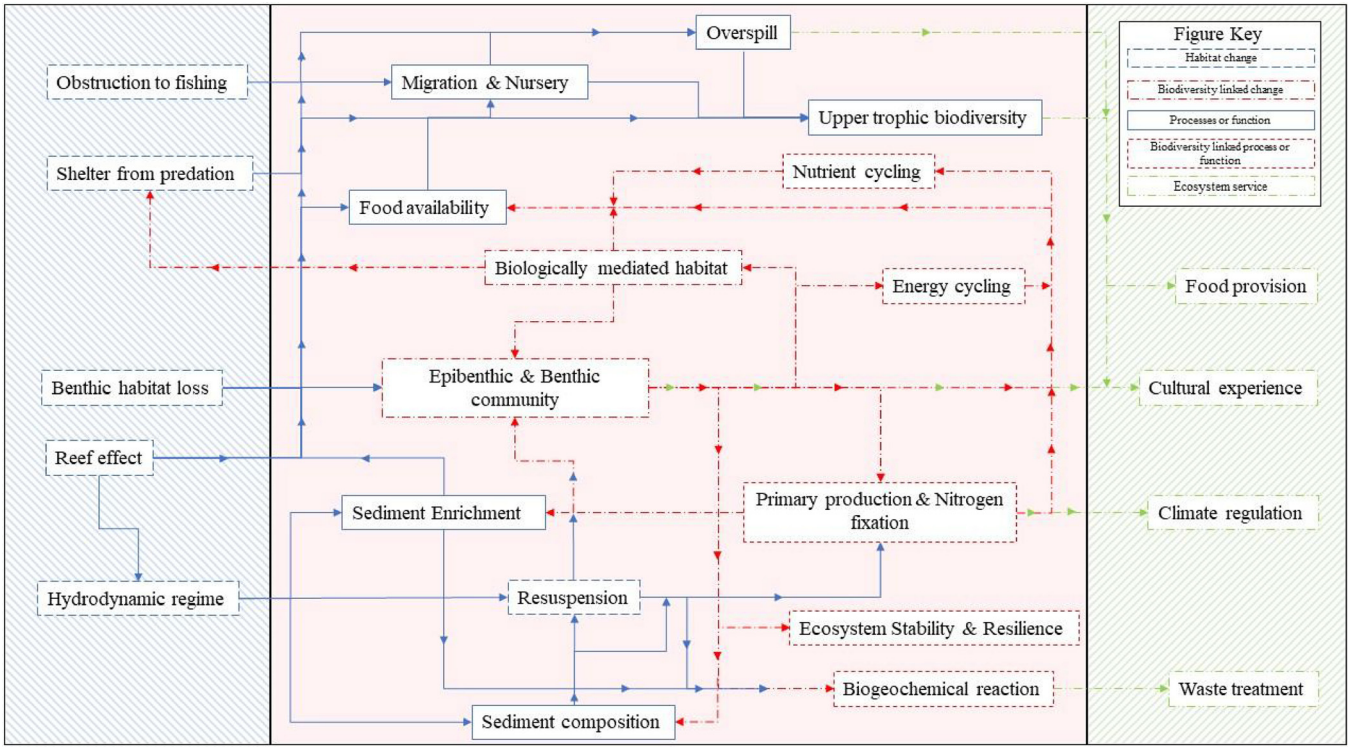

Fig. 1. Biodiversity mediated linkages between habitat modification, ecosystem processes and functions, and the provision of ecosystem services in relation to offshore wind farm structures. Zones represent direct changes (blue hatching – left), secondary changes effecting processes and functions (red – centre), and linked ecosystem services (green hatching – right) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

This higher productivity and nutrient cycling are likely to have positive effects on the availability of food to higher trophic levels (Fig. 1), including commercially important species. Hence, changes in benthic and epibenthic biodiversity may well have knock on effects to food provision and cultural experience of iconic species, such as marine mammals or birds.

In the case of floating OWFs, owing to the greater operational depths, the time taken for organic matter from epibenthic communities to reach the seabed would increase. This is likely to result in the tidal currents spreading organic matter across a wide area and in a finer layer over the seabed. Thus, the localised effect of increased benthic habitat associated with floating OWFs may not be as pronounced as for their fixed counterparts. Alternatively, given consistent littoral fall, in time similar effects to organic matter deposition from fixed offshore wind turbines may become apparent over a wider area.

A further feature of the reef effect is the establishment of secondary or biologically mediated habitat (Fig. 1). For instance, mussel beds provide secondary habitat, increasing environmental complexity and providing further opportunities for feeding and shelter for motile species (Wilhelmsson and Malm, 2008; Krone et al., 2013; Chapman et al., 2005; Krone et al., 2013; People, 2006; Wilhelmsson and Malm, 2008; Witman, 1985). (Witman (1985) found that outside of mussel beds population densities in benthic communities were reduced by 79%. Further there was a reduction in species richness and diversity in all functional groups except mussel bed infauna (Witman (1985).

Although valued for its ability to support other goods and services, biodiversity is culturally appreciated for its existence irrespective other benefits derived from it (Mace et al., 2012). Determining the ecosystem service value of biodiversity may be unclear, but it intrinsically has plausible benefits, and this may then bring a new aspect to considering the advantages of OWFs. Busch et al (Busch et al., 2011) illustrated possible benefits to human wellbeing from significant wind farm development. Interestingly, they identified conflicting views between stakeholders and highlighted ambiguity within the ecosystem services concept. Whilst installation of a physical structure also creates shelter from predation, turbine substructures are also an obstruction to fishing. Busch et al (Busch et al., 2011) reported that the fishing community viewed OWFs as an barrier to fishing, whilst conservationists felt that, by reducing fishing access, OWFs could encourage the recovery of commercially exploited species (Federal Agency for Nature Conservation, 2004; Busch et al., 2011). In providing protection for migratory populations and juveniles, OWFs could support upper trophic biodiversity and allow overspill from commercially exploited populations to surrounding fisheries. This would support food provision to humans and cultural experiences, such as fishing or the enjoyment of wildlife (Fig. 1).

There has been suggestion of co-use of OWF for aquaculture of blue mussels (*Mytilus edulis*), oysters (*Ostrea edulis* and *Crassostrea gigas*) and algae (*Laminaria saccharina* and *Palmaria palmata*) (Miller-Cieluch et al., 2009; Buck et al., 2004). It has been noted that without the foundations of wind turbines as anchor points, extensive aquaculture in the high-energy environment of the North Sea would not be possible (Buck et al., 2004). Although currently a concept, should such co-use become a reality it may help change the attitudes of the fishing community towards OWFs.

Changes in epibenthic biodiversity are likely to be strongly linked with climate regulation and waste treatment (Fig. 1). Increased biodiversity and biomass due to the reef effect around wind turbine substructures and scour protection may lead to greater storage of organic carbon (Lange et al., 2010). Through increased carbon storage OWFs could result in bottom up effects on climate regulation. Moreover, changes in biomass and biodiversity, such as the introduction of mussel beds, are likely to locally enhance water quality and waste treatment due to filter feeding (Lange et al., 2010; Hooper et al., 2017). Yet, at present, the extent to which climate regulation and waste treatment may be altered by the introduction of OWFs is not known. Along with understanding chlorophyll-a as a measure of primary production, there is a need for empirical measurements of nutrient concentrations and the

biomass of filter feeders in epibenthic communities on and around wind turbine substructures. A comparison of the cause-effect pathways leading to changes in primary productivity, nutrient concentration and filter feeding between OWFs and natural habitats, such as portrayed in Fig. 1, would go a long way towards elucidating these effects.

5. Conclusion

By linking changes in biodiversity with ecosystem services we have attempted to highlight potential benefits from OWFs beyond low CO_2 energy production. However, whether changes in biodiversity will have positive, negative or neutral effects on ecosystem services is unclear, as is the magnitude and extent of such effects.

As the offshore wind industry continues to expand we can expect further large-scale modification of the marine environment. Empirical evidence is needed to gauge the scale of the effects of OWFs on biodiversity. However, it should be appreciated that ecosystem services are largely a product of natural processes and functions. Thus, to better understand how OWFs influence ecosystem services we must first consider their effects on functional diversity. Such insight could provide a mechanism for environmental monitoring programmes that are inclusive of ecosystem services and have clear objectives to predict positive as well as the negative impacts.

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